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The Potential for Debris Flows from Karaka Stream at Thames, Coromandel

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

Since its founding in 1867, Thames has been repeatedly flooded by debris-laden water from mountain torrents that drain through it (Summary table). Substantial engineering works lessen the flooding frequency, but they do not mitigate the damage in the rare events that exceed their design capacities or clog the channels with debris. Thames also has a debris-flow hazard from several streams, although it has not been hit by a debris flow in its 138-year history. Events recognisable as involving debris flows have occurred in the upper catchment of Karaka Stream at least four times since 1867, and Thames has been affected by the associated downstream flood of debris-laden water. Of more concern however, is evidence for much larger debris flows reaching the Thames area perhaps 10–20 times in the last 7000 years. Parts of Thames are on debris-flow deposits, and nothing has changed in the environment to inhibit debris flows in the future.

It is not normal in our society to protect, other than by insurance, individuals' assets from very rare hazardous events that may never occur during the lifetime of the asset or even of the individual. To comply with currently recommended New Zealand Building Standards, most buildings in Thames should be able to stay upright and maintain life safety of their occupants in events that might happen only once in 500 years. Society, however, adopts higher standards for valued, or critical community assets, or for single assets when failure would endanger many lives. For these reasons, levels of risk that may be accepted by individuals are not generally accepted for large groups of people, or smaller groups of vulnerable people. Under the recommended building standards, buildings capable of holding large groups, or groups of very vulnerable people should maintain their life safety in up-to once-in-1000-year events, and a few buildings with post-disaster functions to once-in-2500-year events.

The average recurrence interval for debris flows in the Karaka Stream catchment is about 35 years, but the recurrence interval for debris flows large enough to reach out onto the fan (and into Thames) is much greater than 100 years, and could be 500 years or longer. Climate change may increase the debris-flow frequency, but not observably so in the uncertainty of our ability to estimate it. Karaka Stream debris flows are triggered by very high-intensity rain over relatively short durations of 10 to 30 minutes or so, and there are upper bounds on the intensities that can be sustained for such times because of the capacity of air to hold water vapour at various temperatures. Likewise, the capacity for a debris flow to mobilise sediment is limited to what is available to be mobilised, and so, debris flows of 1000-year and 2500-year recurrence intervals probably are not a great deal larger than one of only 500-year recurrence interval.

Debris flows reaching beyond the fan head into the area now occupied by Thames can have total volumes of solid material (including organic debris) in the range of 10^5–10^6 m^3. More than half of the material is likely to be sand and silt, and about half the volume will be carried beyond the limits of the debris flow (in the vicinity of the Thames Hospital complex) and spread as a debris flood through what is now the central business district to the sea. Existing mitigation works would be overwhelmed and become ineffective in such events, which greatly exceed their design capacity.

Karaka Stream is not the only stream at Thames with a debris-flow hazard, but it is the only stream where debris flows directly threaten a major facility in continuous 24/7 use where evacuation with perhaps only 10 minutes warning is impractical. For a 54-bed hospital, the currently recommended Building Standards expect life safety to be maintained in events of up to 1000-year recurrence-interval. If the hospital were to be a designated emergency shelter, or have any other post-disaster function, the even higher life-safety standard up to 2500-year recurrence interval would apply.

Because the substantial Thames Hospital complex is at the likely farthest reach of past debris flows, and because it has a large flat car park and grassed area on its upslope side that will slow future debris flows, we believe that protective measures can be provided for the complex to ensure that lives will not be in danger in it during such extreme debris flows. Such protection for the complex would stop debris flows and divert debris-laden floods around the hospital buildings. It would not protect the Thames central business district from future very damaging debris floods.

Summary Table Historical and future Karaka-Stream hazard events.

Year	Event	Return period	Description**	Impacts	Comment
Prehistoric	Debris with floods	Long, perhaps greater than 500 -year	Exceptionally torrential rain ~3 mm/min sustained for 15 to 30 minutes triggers many debris avalanches in the hills	Metres-high wall of mud, boulders and trees pours out of the upper catchment of Karaka Stream, destroying forest to reach past the area now occupied by the hospital. Forests down to the sea flooded with water, mud and sand.	The upper part of Thames around the hospital is a debris-flow fan, and has been covered by bouldery debris-flow deposits 10–20 times in the last 7000 years.
1867	Thames founded	Once and forever	A rich mining town	Water has high value and is in demand. Town filled with skilled water engineers. All available water is controlled and sold. Streams limited to minimal space.	This sealed the fate of Thames to be dogged by flooding, with no easy, cheap or practical solution.
1881	Flood	~50-year	Torrential rain	Streams overflowed with little warning	Channel work upgraded*
1893	Flood with debris	~100-year	Heavy rain, thunder and lightning	Worst flooding to date. Huge trees rolled through the streets and some areas under 3 feet of water. Karaka Stream rose 5 feet in five minutes	Channel work upgraded*
1917	Flood with debris	~50-year	Cloudburst over the mountains	No warning as thousands of tons of debris carried by the torrent blocked channels which overflowed and flooded the town	Channel work upgraded*
1936	Flood	~20-year	Heavy rain	Flooded streets and businesses	Channel work upgraded*
1960	Flood	~10-year	Heavy persistent rain	Flooded homes, businesses and main shopping centre	Channel work upgraded*
1981	Flood with debris	10-20-year	Torrential rain	Mud, rocks and debris through homes.	Channel work upgraded
1985	Flood with debris	20-year	Torrential rain	Raging torrents through Thames. Hospital, shops and homes flooded	Channel work upgraded
1988	Cyclone Bola	~5-year	Heavy rain		Thames missed the worst of the cyclone
2002	The weather bomb	~100-year	Exceptional rainfall	Highest flows, but torrent “controlled”	Channel repaired By chance, no large debris avalanches were triggered in the Thames catchments
Missing for a town with ~140-years' of history	Floods with debris	>100-year	Torrential rain	No warning as thousands of tons of debris carried by the torrents block channels which overflow and flood the town	Implies that the return periods of some of the above events may be underestimated

Yet to come	Debris with flood	~500-1000 years	Exceptionally torrential rain, perhaps ~3 mm/min sustained for 15 to 30 minutes, probably, but not necessarily following shortly after a wet period of exceptional duration.	Widespread flooding. Metres-high wall of mud, rocks and debris races into the Thames Hospital grounds. Homes, and businesses destroyed. Debris flows could pour into Thames from any or all of the catchments above the town. Thames is not likely to be the only community severely hit by the storm.	With the current lined channel through town, Karaka stream can carry the ~100-year floodwater, but only if there is no debris with it. The return period of debris volumes exceeding the upstream sediment-trap capacity is unknown, but is unlikely to be more than 100-years.

* Inferred as a likely course of events in an *ad hoc* world.
** Description as given in historical record unless otherwise specified.

The conclusions from our study are:

- The town of Thames has developed on a series of large debris-flow fans, but it has yet to experience a debris flow entering it since its founding in 1867.
- Debris flows have occurred in Karaka Stream at least four times in the last 138 years. The sediment and organic debris washed from them have made the associated downstream flooding in Thames worse than if there had been only the floodwater.
- The return period of such debris floods in Thames was about 35 years. The return period has been increased by mitigation work, but not greatly so.
- In the last 7000 years, many (~10–20) large debris flows (~100,000–1,000,000 m^3) have reached the area now occupied by Thames Hospital. The return period of large debris flows capable of reaching into Thames is much greater than 100 years, but less than 1000 years.
- Existing mitigation work on Karaka Stream can safely carry water flows of at least 100-year return period when there is little sediment, but it is not able to cope with large sediment influxes (~100,000 m^3 and greater) likely to be associated with future debris flows, whether or not a debris flow reaches the fan head at the upper Thames Hospital car park.
- The effect of a major debris flow on the Thames Hospital complex currently is partly mitigated by the upper car park and grassed area. The effect of these could be exploited to ensure that the building complex remains safe for patients and staff during any future debris flow. This could be achieved by designing the area as a non-water retaining, debris-storage basin, and ensuring that sediment-laden water can pass around the building complex without entering occupied hospital buildings.
- The hospital emergency water supply is stored on the debris-flow fan head and is vulnerable to any future large debris flow that takes out its source or storage tanks.
- Safety requirements for the hospital exceed those for most of the remainder of the town. Providing measures to ensure life safety at the hospital during a major debris flow should eliminate the direct debris-flow danger downstream of the hospital and not make the flooding and debris-flood hazards worse.
- If areas downslope of the hospital complex desire greater protection from flooding, it is

most easily achieved by trapping more sediment upstream of the hospital, and even upstream of the fan head , but protection from events much above 100-year return period may be impractical, and some form of warning system, with time to evacuate, should be considered.

- Improvements to New Zealand's weather radar system currently being implemented by the New Zealand Meteorological Service should enable Severe Weather warnings to be issued within ~10 minutes, as severe weather evolves, and potentially before a debris flow is initiated. Once initiated, debris flows can be detected through sonic-range ground vibrations using currently available technology. Automated detection could give a few minutes' warning, enough to evacuate the immediate impact area above and including the hospital car park.
- The currently proposed site for the new wing of the Thames hospital is suitable provided the building is well constructed and protected from direct debris-flow impact.

We recommend that:

- The Thames community considers the implications of future major flooding with debris in the central business district and elsewhere, and determines agreed levels of affordable protection that they may not currently have. Achieving this level may require additional sediment traps in Karaka Stream and elsewhere.
- The Thames community makes use of the future capacity of the New Zealand Meteorological Service to provide effective severe-weather warnings.
- The Thames community considers the practicality of implementing debris-flow detection systems on Karaka and Hape Streams
- The Thames Hospital management notes the vulnerability of the hospital's current emergency water supply in extreme floods and debris flows in Karaka Stream.
- The area in the vicinity of hospital upper car park be re-fashioned to function additionally as an effective debris-flow storage basin, with a large, high bund against the new wing. The intention of such bund is to cushion the new building against a direct hit by a debris flow and to safely deflect debris-laden floodwater (and any additional debris-flow volume) around the entire hospital-building complex.

1.0 INTRODUCTION

Since Thames' founding in 1867, it has been repeatedly flooded by debris-laden water from streams that drain through it. This will continue, but with lower frequency because of substantial mitigating work. In addition to the obvious flooding hazard, Thames has a debris-flow hazard, even though the town has not been hit by a debris flow in its 138-year history. Events recognisable as involving debris flows have occurred in the upper catchment of Karaka Stream at least four times since 1867, and Thames has been affected by the associated downstream floods of debris-laden water. Of more concern is evidence for very much larger debris flows reaching the area now occupied by Thames township, perhaps 10 to 20 times in the last 7000 years; that is once in 350 to 700 years on average. Many of these debris flows appear to have been as big as, or larger than the largest of the recent ones at Matata in 2005, and much larger than fatal debris flow at Te Aroha in 1985. Such events in Thames today would be disastrous.

To meet currently recommended New Zealand Building Standards, family dwellings and most buildings in which fewer than 300 people might congregate should remain serviceable in events that might happen only once in 25 years on average, and maintain life safety for those in them in events that might happen only once in 500 years. So in Thames, such buildings are easily compliant with the serviceability standard, but might be only marginally compliant with the life-safety standard should they lie in a possible debris-flow path. Schools with capacities greater than 250 and health-care facilities with capacities of 50 or more resident patients have similar 25-year serviceability requirements, but should maintain life safety in events up to once in 1000 years, and so would be non-compliant for life safety if they lay in a Thames debris-flow path. Structures with recognised post-disaster functions – such as fire and police stations, designated emergency shelters and emergency-vehicle garages should remain serviceable in events that might happen only once in 500 years on average, and maintain life safety for those in them in events that might happen only once in 2500 years. Existing structures with these functions around Thames are likely to be serviceable after a major Thames debris flow, only if they are beyond the reach of it and its downstream flood.

After 138 years, that have included numerous major floods with severe damage to the central business district, the people of Thames have yet to gain a solution to their problem of dealing with sediment-laden flood runoff, when channel capacities are exceeded, or channels become choked with sediment. Many New Zealand communities have engineered storm-water systems with design capacities limited to the 25-year event (the widely accepted serviceability standard), and some engineered river systems are intended to safely carry significantly larger events (60–yr, 100-year and even higher). Whatever the choice of probability, such designs carry the implicit understanding that the capacity of the system will be overwhelmed on occasion by events that exceed the design capacity. A necessary, and often neglected part of this widely accepted design philosophy is to consider what happens when events exceed those for which the scheme is designed. There is a growing belief that good hazard-mitigation work should not make a situation significantly more dangerous when a larger-than-design event inevitably occurs. Also, the mitigation work should not in itself create a danger when overwhelmed. The September 2005 flooding of New Orleans, USA, highlights the dangers that well-intentioned engineering work can create. Thames can expect the present Karaka Stream scheme, designed for the once-in-60-year event, to be overwhelmed several times in the next 138 years, and eventually, it will be overwhelmed by a debris flow, which was not considered in its design.

Debris flows are unfamiliar to the New Zealand public. 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 initiate in other ways; when the rainfall intensity is high enough, the natural subsurface drainage system on slopes 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 on 17 February, 1985, at Te Aroha, and on 18 May, 2005, in the catchments behind Matata. There are other ways that debris flows can form, but they are not of concern here.

In New Zealand, debris flows do not usually occur without associated flooding downstream. Although debris flows were the primary hazard at Matata on 18 May 2005, they were accompanied by major flooding too. Thames has a similar problem. Because debris flows are one of the more destructive natural hazards, now that the hazard is recognised, there is need for the people of Thames 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 with severe-weather warnings and evacuation. The important thing is to have no people and few homes in the way of future debris flows; debris flows are lethal and destructive.

1.1 Purpose and scope of the report

This report is on the natural processes that might lead to, and follow a debris flow at Karaka Stream, Thames. It has been prepared by Dr Mauri McSaveney and Mr Dick Beetham of GNS Science, for Environment Waikato. 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[i]. 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. Together, they have recently reported on the May 2005 debris-flow disaster at Matata[ii].

This report's objective is to present an analysis of geological and runoff processes likely during extremely intense rain in the catchment of Karaka Creek, and to assess likely future risks and their consequences to Thames. The purpose is to provide Environment Waikato and the people of Thames with background to enable informed decisions on future land use around Thames.

This report presents:

- the results of analyses and investigations of past storms and their consequences based on reports, a site visit and discussions with others;
- scenarios for future events with likely debris flows and their extent at Thames;
- possible mitigation measures.

Dr McSaveney and Mr Beetham inspected the area on 21–22 November 2005. We have examined vertical aerial photographs taken in 1944, 1961, and 1981, and a number of reports listed in Section10.0.

1.2 The Brief

This report has been prepared for Environment Waikato in accordance with a brief determined by Mr Adam Munro, River Projects Manager, EW. and others in consultation with Dr McSaveney and Mr Beetham. The brief is as follows:

Brief:	Karaka Stream Debris Flow Hazard Assessment
Issued to:	GNS Science
Objective:	To provide an analysis of the geological and runoff processes in the Karaka Stream catchment under extreme rainfall conditions, and assess likely future risk and consequences.

Scope of Services:

1. To identify the potential causes of major debris-flow events on the Karaka Stream in Thames.
2. To assess the main catchment (Karaka) and the slopes behind and above the town, in terms of historical events and the likely processes that could result in significant 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. Seismic activity and its effect on stability and erosion potential;
d. Sediment-transport processes active during storm events;
e. Possible damming of debris in streams;
f. Channel erosion.
    1. To estimate the quantity of solid material and debris that could be delivered from the catchment including its likely flow path(s) and impact on existing flood scheme (namely the debris trap and channel works).
    2. To comment on likely catchment response to hydrological events in:
        - The immediate term, in relation to sediment 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.
    3. To delineate the area of risk from debris-flow and debris-flood deposition downstream of the catchment outlet upstream of the town
    4. 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 from previous events
- scenarios for future events with likely debris flows and extent on Thames township
- possible mitigation measures

Liaison:

- EW & TCDC for survey information, historical records of flooding, hydrological/hydraulic data, cadastral boundaries, present and future land use/zoning and tenures, high resolution photographic imagery and LiDAR

Delivery:

- Interim report by 1 December 2005
- Draft report by 23 December 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 particular types of landslides. For example the authoritative landslide reference texts “Landslides - Analysis and Control” [iii], and its updated edition “Landslides: Investigation and Mitigation” [iv], 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[v].

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. Debris flows have occurred in many New Zealand localities, causing deaths at Blandswood, Te Aroha, Klondyke Corner, Motueka, and the Rees Valley. The most recent debris flows of note were at Matata on 18 May 2005 where fortunately there were no fatalities (Figure 1.3.1). There is geomorphic evidence for prehistoric debris flows at Thames, but none have entered the town in historic time.

Figure 1.3.1 At Matata, the evidence for past huge debris flows is easy to read in the landscape because a very recent “translation” has been provided. Recognition of this evidence before 2005 could have allowed opportunity to avoid 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. Damaging debris floods occurred recently at Paekakariki, north of Wellington during intense rain storms in October 2003 (Figure 1.3.2), in February 2004 and in January 2005[vi.] Debris floods have occurred at Thames as the downstream consequences of debris avalanches and debris flows in catchments east of the town.

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

- A debris avalanche (Figure 1.3.3) 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. Debris avalanches are a very common form of storm-triggered landslide and have occurred widely through the Coromandel and Kaimai Ranges in recent major storms such as those of 1981, 1985, and the Weather Bomb of 2002.

Figure 1.3.3 Debris avalanches near Matata. Debris avalanches such as these initiate debris flows when they fall into 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. Many large, dense boulders are available in the bed of Karaka Stream. They only move significant distances during rare debris flows. The homes are on a terrace that is the top of the Karaka Stream debris-flow fan.

Figure 1.3.6 Organic debris from the catchment forest cover is estimated to have been about 10% of the total debris carried by debris flows at Matata in 2005. As at Karaka Stream, the forest was regrowth after milling, but the condition of the vegetation at Matata played no useful mitigating role in the extreme event which overwhelmed any forest protective capacity. The forest cover at Karaka Stream is well able to mitigate small debris avalanches, but can be overwhelmed in larger events.

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 legal principle of *proximal cause* would also support this technical usage in law.

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, is not a reliable guide, because buildings can be structurally damaged by rolling boulders in the debris-flood phase downstream of the debris flow on fans as steep as the upper fan segments at Thames.

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. This is what occurred at Matata on 18 May 2005, and it is what made those debris flows so large by the time that they reached Matata.

Debris flows 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 and its associated debris flood 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 easily be overwhelmed.

Another useful term in the context of debris flows is *hyperconcentrated flow*[vii]. 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 floods, 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.

1.4 Debris flows and 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, usually an active one, or one with a recent history of activity. Much of the rock east of Thames was erupted from various vents of an ancient volcano some millions of years ago, and so it is stretching the *lahar* concept to apply it to debris flows in the catchments behind Thames. The correct term for such events at Thames is *debris flow*.

1.5 Relevant terms in New Zealand statutes

To put the above terminology into a New Zealand legal context with respect to Thames, 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 Thames 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. An avulsion of Tutumangao Stream is what turned the 1985 event at Te Aroha into a tragedy. *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* is a natural hazard 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 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* could be viewed as the principal natural hazard covering *debris flows* which are a type of *landslide*.

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.

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 Thames.

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 are 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.

In all technical treatises, *debris flows* are a type of landslide. They are not a type of *flood*.

1.6 Relevant New Zealand Standards for Structures (AS/NZS 1170.0:2002)

Debris flows are life threatening and can be structurally damaging to buildings they impact on, and not merely an inconvenience, briefly affecting service, 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 currently recommended standards associated with the Building Act (2004) (AS/NZS 1170.0:2002) it is appropriate to locate and construct dwellings and most structures 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 for the debris flow of 10% probability in 50 years (an event of 500-year return period or 1/500 Annual Exceedence Probability (AEP)), whereas for protection from the inconvenience of non-structurally damaging flood inundation, lower levels of protection may be appropriate (such as the 1/25-, 1/50- or 1/100-AEP). Where floods can destroy buildings and threaten lives within them, however, there is no rationale for treating them differently from the other similarly destructive and dangerous hazards that may strike with little warning.

For lifeline structures such as police and fire stations, emergency-vehicle garages, designated emergency shelters, and hospitals with designated special post-disaster functions for their emergency and surgical facilities, a much higher standard of safety is expected, and compliance with currently recommended New Zealand Building Standards (AS/NZS 1170.0:2002) requires that such buildings are still able to provide their services after a disaster of up to 500-year return period, and do not endanger their occupants in even more extreme events up to 2500-year recurrence interval (1/2500 AEP), even though the life-expectancy of such buildings still is only 50 years.

Between these groups of building uses and standards is another group that may involve crowds of people, and hence may pose risks to many lives, or they may have highly valued functions in society. They don’t need a high level of reliability for service, but their recommended life-safety standard is 1/1000 AEP. The more vulnerable are the group of people, the smaller the number that constitute a crowd.

AS/NZS 1170.0: 2002 is not yet mandatory, but it follows current best practise and is recommended and widely accepted for structures.

2.0 ASSESSMENT OF CATCHMENTS AND PROCESSES CONTRIBUTING TO DEBRIS FLOWS

2.1 Geology

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

2.1.1 Mantling deposits around Thames

The surficial materials mantling the landscape around Thames are entirely derived from weathering of volcanic rocks: the subaerial volcanic rocks of long-dormant, ancient, Coromandel volcanoes. Thicknesses of the weathered mantle vary widely and unpredictably, from zero to many tens of metres. Soils on the steeper slopes are generally shallow and stony, but are locally deep and stony over landslide deposits. Shallow and deep landslides are widespread on the Coromandel Range. None of the original volcano topography remains.

2.1.2 Kuaotuna formation

The oldest exposed rock in the vicinity of Thames is the volcanic Kuaotuna formation. This consists mostly of andesite and dacite intrusives and flows with coarse airfall deposits between flows. The volcanism ranges in age from 11-18 million years (Early to Mid Miocene). These volcanic rocks are extensively altered by the long-past passage of highly acidic, hot water. This formation contains many quartz veins, extensively mined for gold and silver. Most of the boulders in the bed of the streams come from the less altered members of this geological formation. The more hydrothermally altered rock has been changed to a white to light grey, only moderately hard rock that readily weathers to a thick, soft soil, prone to creeping downslope as large landslides called earthflows.

All of the Karaka catchment east of Thames is underlain by Kuaotuna formation.

2.1.3 Waiwawa formation

Like the underlying Kuaotuna formation, these hydrothermally altered volcanic rocks also are mostly andesite and dacite flows with tuffs and volcanoclastic breccias between flows. They differ from the Kuaotuna formation mostly by being significantly younger (6 to 10 million years, Late Miocene). At Thames, they outcrop mostly to the southeast end of the town. They tend to be less altered that the older Kuaotuna formation, and are notably lacking in gold mineralization.

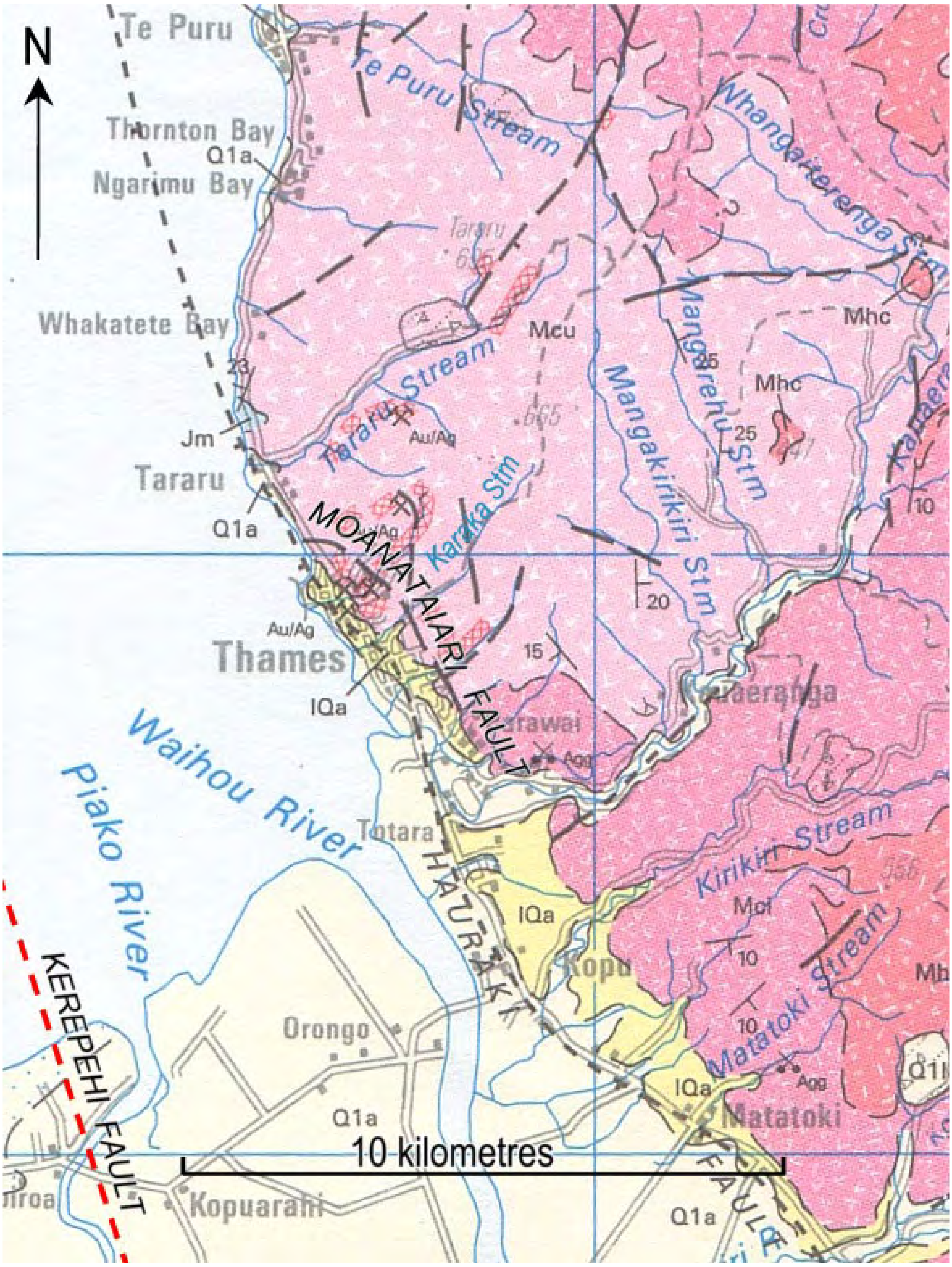

Figure 2.1.1 Geological map of the Thames area showing the distribution of the geological formations discussed in the text, and the major faults recognised in the area. Mcu is Kuaotuna Formation of andesite and dacite flows and tuffs, hydrothermally altered and with gold (Au) and silver (Ag) mineralisation. XXXX is major mineralised quartz vein. Mci is Waiwawa Formation of andesite and dacite flows and tuffs, hydrothermally altered but without gold and silver mineralisation. Mhc is pumice-rich ignimbrite. lQa is late Quaternary fan deposits. Q1a is Swamp/peat deposits. Approximate location of active Kerepehi Fault is inferred by extrapolation of recent trace to South of map area. Data from GNS files.

Figure 2.1.2 Topographical map of the Thames area. Section of Topographic map 260-T12 Thames (2001). H is location of Thames Hospital. Grid spacing is 1 km.

2.1.4 Fans and stream deposits

The central part of Thames is built on fans of sediment washed out of the steep catchments above Thames and deposited on the gentler gradients of the fans at the coast. The coastal portions of these fans are composed of coarse and fine sediment washed out from the catchments when the streams were in fresh and flood – in these areas they are alluvial fans. The upper portions of the fans are steeper and composed of beds of coarser sediment with some large boulders, sandwiched between layers of finer sediment similar to that on the lower fans - these portions are debris-flow fans. Although the highest portions of Thames are built on surfaces tens and hundreds of thousands of years old, most of Thames is built on surfaces deposited in the last 7000 years since sea level stabilised at about its present level after rising from levels up to 120 metres lower in the last ice age.

2.1.5 Anthropic deposits

Much of the sea frontage of Thames is land reclaimed from the sea by infilling with waste rock from mining. For Moanataiari and Wiaotahi Streams in particular, this has greatly reduced their lower-reach gradients, inhibiting any ability to route sediment through their channels to the sea.

2.1.6 Source of the boulders

The boulders in the stream beds come from the less altered andesite and dacite flows of the Kuaotuna formation. Boulders to 3 metres in diameter are present on the bed of Karaka Stream (Figure 1.3.5). These lie on hard bedrock, and potentially are relatively easily mobilised by large debris flows. They may roll over occasionally due to scour in major floods, but they only move significant distances during large debris flows.

2.1.7 Faulting in the Karaka Stream catchment

An ancient fault, the Moanataiari fault crosses the lower portions of Moanataiari, Waiotahi and Karaka Streams. It crosses Karaka Stream just upstream of the Irishtown bridge and fractured rock is exposed in the stream bed there. The exposed rock in the stream bed to the west of the bridge is fresher and less fractured than rock immediately upstream. Fraser (1910) maps this fault as a major structure dipping at 45° to the southwest, with the rock to the southwest of the fault downthrown relative to the rock to the northeast. The bedrock here is locally more easily eroded because of the fractures, but this is not likely to contribute significantly to debris-flow generation.

2.1.8 Regional faulting and earthquakes

The area that forms the Firth of Thames is part of a geological structure called the Hauraki rift, an area where rock has dropped down between systems of earthquake faults. The Firth has formed because the eastern and western sides have moved away from one another. Thames lies on the eastern edge of this geological structure, in the midst of a zone of faults collectively known as the Hauraki fault that includes the Moanataiari fault.

The Hauraki fault is not known to be active. The only recognised active fault near Thames is the Kerepehi fault which bisects the Hauraki Plain and the Firth of Thames. The Hauraki fault, however, traverses a more geomorphically active environment than does the Kerepehi fault, and so if it has had geologically recent movement, traces of its last surface movements could have been removed from the landscape. It is improbable that the two adjacent fault systems have widely dissimilar levels of activity.

The faulting has provided the steep local relief between the headwaters and the sea, and set the scene for development of the relatively short steep catchments, but it does not contribute directly to the generation of debris flows. Strong ground shaking is both highly unlikely to occur, and unlikely to cause debris flows when it occurs.

2.2 Geomorphology of Karaka Stream

Much of the central business district of Thames lies on a composite fan deposited by Karaka Stream. It is composite because its upper and lower parts are formed dominantly by two different processes. The upper section of this fan, from the Irishtown bridge to downstream of the Thames Hospital is a debris-flow fan, built mostly by debris-flow deposition. The lower section, down to the reclaimed land along the foreshore, is a simple alluvial fan, built mostly from sediment reworked from debris-flow deposits. Karaka Stream currently is incised into the debris-flow fan above the hospital grounds.

The steepland catchment of Karaka Stream to the northeast of Thames is the largest and most deeply incised of the steepland valleys east of Thames. The stream is a pool-and-riffle mountain torrent, and lies in a deeply incised U-shaped canyon in the valley bottom. The channel cross-profile is typical of those cut by infrequent debris flows. It has two unusual characteristics: it is unusually wide; and it is largely devoid of any large storage of bed material in the kilometre of channel upstream of the Irishtown bridge that we inspected. The shortage of sediment storage appears to reflect depletion of in-channel sediment in recent storms. It indicates that few new sediment sources have opened up in the last few decades.

The wide debris-flow channel in the catchment indicates that it has been cut by recurrent very large debris flows. The flows that cut this channel were far larger than could now fit through the incised gorge section of Karaka Stream downstream of the Irishtown bridge. This is not surprising because the gorge is incised through the deposits of the last very large debris flow into the bedrock below.

While the channel is in a state of depleted sediment storage, there is a reduced potential for large debris flows in the short term, because it requires a particularly large storm, or sequence of smaller storms to replenish the in-channel storage and thus restore the potential for easy generation of large debris flows. Although the potential is reduced, the possibility is not eliminated, and the storm that replenishes the storage, could be the storm that generates the large debris flow.

Previous fans of the Thames streams were trimmed by the rising sea until sea level stabilised at about its present level some 7000 years ago. The trimming formed a low coastal cliff (and in places more recently trimmed by Kauaeranga River). This former cliff now is just a relatively steeper slope through Thames (Figure 2.2.1). Since 7000 years ago, sediment from the Thames streams have partially reconstructed the trimmed portions of the fans. Trimming caused Karaka Stream to cut deeply into the toe of its fan, and it has since deposited a smaller fan, at the apex of which is the Thames Hospital site.

Of course there were fans and debris flows before 7000 years ago, but this time when sea level stabilised after rising rapidly from the low level of the last ice age provides a convenient reference datum for assessing the geomorphic change that has occurred since that time.

In addition to the main debris-flow channel in the valley bottom, many of the minor tributary channels perched above the U-shaped canyon, also are broadly U-shaped, indicating widespread recurrent debris-flow activity at many scales in the catchment. Further, the landscape of the upper catchment is one of very steep-sided sharp ridges with gentler, rectilinear slopes down the upper slopes of the steep-sided canyon of the valley floor. This is a typical morphology for a landscape dominantly sculptured by debris avalanching during heavy rain. It is a common landscape through the Coromandel and Kaimai Ranges.

2.3 Other streams at Thames

There are six stream fans of main concern to Thames, the fans of Moanataiari, Waiotahi, Karaka, Hape, Herewaka and Waikiekie Streams (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 Te Aroha and Matata. Such events do not happen often, but they occur frequently enough to have built the existing fans in the last 7000 years. The deposits of a past debris flow can be viewed in the upper parts of the banks of Karaka Stream below the Irishtown bridge.

Of the six streams, the larger catchments have the greater risk. Not only are the debris flows likely to be larger in a given event, but the probability of a given storm triggering a debris avalanche to transform into a debris flow varies directly with the area of susceptible slope in the catchment, and so a larger catchment is more likely to have at least one debris avalanche, and hence is likely to have debris flows more frequently. Larger debris flows can be triggered by larger debris avalanches, but they are more likely to be triggered by multiple debris avalanches, as occurred at Matata in May 2005.

North of Thames, there are many small coastal streams draining from steep slopes exposed to similar levels of high-intensity rain. All are susceptible to debris avalanches and debris flows, but again, the probability is in proportion to their catchment area. The debris flows are a danger because the catchments are small, but large enough that their streams have cut to the foot of the ancient sea cliffs, so that the larger debris flows can run out onto fans along the sea shore. Because debris flows are rare events, these easily developed fans gave an illusion of safety that encouraged development. Elsewhere similar, but unoccupied, debris-flow fans still give this illusion.

The larger coastal catchments further to the north of Thames (Tararu, Te Puru Streams, and Tapu and Waikawau Rivers) are too large for debris flows in them to propagate to the coastal plain – so the river-related hazards there relate only to flooding and debris floods. Although the coastal settlements at their mouths have severe flood hazards, they do not have debris-flow hazards. Waiomu Stream is unusual because although its catchment is similar in size to

Karaka Stream, it appears to have too low a gradient in its lower valley for debris flows to reach its coastal fan. Debris-avalanche and debris-flow hazards for these rivers and streams are restricted to the upper valleys, and the lower reaches have only high debris-flood and flood hazards.

2.4 Effects of geology on headwater slope stability

The hydrothermally altered andesites, dacites and their associated interbeds range widely in erodibility. The harder rocks stand in high, steep, to very steep slopes forming the deep narrow stream channels which are floored mostly on hard andesite and dacite. Even the hardest rocks are cracked from contraction during cooling from high temperature. These cracks promote failure of the even the strongest rock in the catchment, and the formation of many large to very large boulders in the stream bed. The largest of these boulders are too large to move in normal stream flood flows and are moved only by debris flows.

The weakest rocks form relatively low slope angles because they are susceptible to creep when wet. It is these rocks that make the catchments particularly prone to debris avalanching, and hence to forming debris flows.

2.5 Storm rainfalls

Raingauges have been read at Thames since 1936 (B75152 since 1957). From 1957 to 1980, the maximum recorded 10-minute rainfall was 22 mm (31 mm for 20 minutes and 36 mm for 30 minutes). These values are similar to the extremes recorded elsewhere in northern New Zealand, but the outlier short-duration rainfalls recorded at Tauranga are probably more indicative of the extreme rainfalls possible at Thames in the longer term (>>100 years)(34 mm in 10 minutes, 51 mm in 20 minutes and 68 mm in 30 minutes). Such extremely intense rainfalls for the longer durations could fall from a very active convective storm in a convergence zone of very warm, moist, tropical air, perhaps localised by the eastern shore of the Firth of Thames and the Coromandel Range.

Sustained rainfall intensities of more than 2 mm/minute are capable of triggering debris avalanches widely over steep slopes in the Coromandel Range including the catchments above Thames, and they will do so most times they occur, and more so if the catchments already are well saturated, such as when an intense burst of rain culminates a much-longer-duration storm.

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

The valleys above Thames are well vegetated in secondary, largely native forest consequent on logging more than 100 years ago. Only a small proportion (a few percent) of the catchment areas are likely to be affected by landslides, debris avalanches and debris flows during any single storm, although in most of the directly impacted areas, the vegetation removal will be total.

Immature forest trees falling from the slopes and eroded from the channel banks will contribute to a large volume of woody debris delivered to the fans in an extreme event, such as occurred in Karaka Stream in 1893, in Te Aroha in 1985, and in Matata in 2005 (Figure

1.3.4). Forest cover will neither inhibit, nor contribute to initiating the debris flows; the trigger will simply be very high-intensity rain that overwhelms any protection afforded by the forest cover.

Root strength is a major factor contributing to the strength of the soils on the slopes, and the root strength of the existing immature forest is little different from that to be expected when the forest cover is fully mature. However, root strength is finite and will be exceeded in rare events. Also, under the extreme rainfall conditions, many of the landslips will be from failure of the bedrock deep beneath the root mass, and so root strength will contribute mostly to the size of the falling masses and little to whether or not they fall under these extreme conditions.

Rainfall interception by forest cover is not a useful mitigating factor in such extreme storms because the forest and soils already will be wet from earlier rain.

Whilst maintaining a healthy forest cover has many beneficial effects, the extreme storms that trigger large debris flows are too extreme, and way beyond the capacity of any forest cover to protect Thames 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.

The above notwithstanding, the risk of debris flows was very significantly heightened by the initial logging, and probably only recently has returned to anything like its pre-logging value.

2.7 Sediment transport processes active during big storms

The primary causative events that will lead to debris-flow damage at Thames will be landslips, mostly debris avalanches — these are relatively thin slabs of weathered rock that detach along cracks parallel to the slope, together with all of the vegetation and soil mass on them, and all, or most of the vegetation and soil mass on the slope below – all the way downslope to the stream channel (a very large one occurred in Te Puru Stream in 1981, and another in Tutumangao Stream at Te Aroha in 1985). 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 are triggered by the catchments' response to very high intensity rain. 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. Above 2 mm/minute and approaching 3 mm/minute they can be expected to be even more widespread in the catchment, and to be larger and deeper. The most susceptible slopes are where either or both of surface and subsurface flows converge — the hollows in the landscape, but at the more extreme intensities, even the more stable noses with diverging water flow, may fail.

As debris avalanches reach stream channels, they may transform 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 scrape the channel floor and sides leaving a characteristic U-shaped channel, as if it had been cut by a miniature glacier.

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 Thames. On such slopes they slow, then stop. The water draining from them can cause a debris flood downstream. 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. Further, the debris flow may have avulsed from the stream channel, so that the floodwater and debris flood may be unmitigated by existing channel works.

Because the floods that often extend beyond debris flows are from the water that has been picked up by the debris flows and transported more rapidly to the fans, the floods are larger and much more extensive that could occur had there been flooding alone, without the debris-flow phases. In effect, the fast debris-flow process speeds up the times of concentration of the flood peaks, resulting in much higher peak flood discharges.

2.8 Debris flows caused by damming of streams

The hydrothermally altered volcanic rocks in the catchments above Thames are susceptible to large-scale creep down slope as large landslides of the type known as earthflows (unlike debris flows, earthflows move relatively slowly). Such earthflows, and many other types of landslides can block small streams such as Karaka Stream, ponding lakes upstream of them. Breakout of such lakes is known to trigger debris flows in small catchments. At Matata, there was much local concern that the 2005 debris flows had been caused by damming of the streams, and subsequent break-out floods. Although this does not appear to have been the case at Matata in 2005, it does not mean that debris flows at Matata (and other towns) can not be triggered by break-out floods. To produce a significant debris flow, however, a relatively large landslide and large lake are required. Exceptionally heavy rain is likely to occur more frequently over Karaka Stream than the occurrence of such larger landslides there.

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 Thames (Figure 2.9.1). Such U-shaped channels in hard bedrock are not formed in a single event, they form over many events. So the presence of a U-shaped channel section in Karaka Stream is convincing proof of many past debris flows.

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

Much of the sediment in debris flows does not come directly from the initial debris avalanches from the valley sides. It is picked up by the debris flows as they erode their channels. The role of the debris avalanches is to initiate the debris flows. Once initiated, debris flows can be self-sustaining and grow quickly in volume in a steep-enough channel, until they reach lowland fans such as at Thames.

2.10 Previous debris flows, and debris-flow recurrence interval at Thames

There is irrefutable evidence for previous debris flows at Thames. The evidence shows that large prehistoric debris flows built the land beneath Thames over the last 7000 years. The last big debris flow formed the land surface on which Thames Hospital now stands.

Table 1 lists nine floods that have occurred in Thames in the last 137 years. Several of these (those listed with flood and debris in Table 1) appear to have been associated with debris flows upstream of the fan head, but no debris flows have entered Thames township. This record appears to be incomplete in some aspects for several reasons. First, the record is almost 140 years long, but the most severe floods are assessed as only up to 100-year recurrence interval (1/100 AEP). It is quite probable that the record contains an event of up to 200-year return period or more (≤ 1/200 AEP), and the true magnitude of the event is unrecognised, because the unquantified magnitudes cannot be plotted in a manner that allows such extreme events to be recognised as outliers in the distribution. Second, aerial photography from 1961 shows an erosion scar of a large debris avalanche in the catchment of Hape Stream that does not appear on aerial photography of 1944, yet no flood with debris is shown in that interval in Table 1.

The historical record, combined with the geomorphic evidence, shows that debris flows reaching Thames township are very rare events of much greater than 100-years recurrence interval. To have had many in 7000 years indicates a return period of some hundreds rather than some thousands of years. Of course within the spectrum of debris flows reaching onto the fan, there will have been some larger and rarer events.

If we count the “floods with debris” as evidence for debris avalanches and debris flows within the catchment, the annual occurrence probability of debris flows in Karaka Stream is 4/138 = 1/35 (~35-year return period). It is more difficult to obtain an accurate estimate of the annual exceedence probability of Karaka Stream debris flows reaching the outskirts of Thames; something in the vicinity of 1/500 (~500-year return period) seems likely to account for the evidence of many in the last 7000 years. Hence, the chance of a major debris flow in Karaka Stream reaching the present Thames Hospital is about twice as great as 1/1000 in any year. On this basis, some mitigation work would be needed if the hospital site, and especially the proposed new wing, were to meet currently recommended standards in AS/NZS 1170.0:2002.

Table 1 Summary of historical[viii] and future events involving Karaka Stream.

Year	Event	Return period	Description**	Impacts	Comment
Prehistoric	Debris with floods	Long, perhaps greater than 500 -year	Exceptionally torrential rain perhaps ~3 mm/min sustained for 15 to 30 minutes triggers many debris avalanches in the hills	Metres-high wall of mud, boulders and trees pours out of the upper catchment of Karaka Stream, destroying forest cover and reaching past the area now occupied by the hospital. Forests down to the sea flooded with water, mud and sand.	The upper part of Thames around the hospital is a debris-flow fan, and has been covered by bouldery debris-flow deposits 10–20 times in the last 7000 years.
1867	Thames founded	Once and forever	A rich mining town	Water has high value and is in demand. Town filled with skilled water engineers. All available water is controlled and sold. Streams limited to minimal space.	This sealed the fate of Thames to be dogged by flooding, with no easy, cheap or practical solution.
1881	Flood	~50-year	Torrential rain	Streams overflowed with little warning	Channel work upgraded*
1893	Flood with debris	~100-year	Heavy rain, thunder and lightning	Worst flooding to date. Huge trees rolled through the streets and some areas under 3 feet of water. Karaka Stream rose 5 feet in five minutes	Channel work upgraded*
1917	Flood with debris	~50-year	Cloudburst over the mountains	No warning as thousands of tons of debris carried by the torrent blocked channels which overflowed and flooded the town	Channel work upgraded*
1936	Flood	~20-year	Heavy rain	Flooded streets and businesses	Channel work upgraded*
1960	Flood	~10-year	Heavy persistent rain	Flooded homes, businesses and main shopping centre	Channel work upgraded*
1981	Flood with debris	10-20-year	Torrential rain	Mud, rocks and debris through homes.	Channel work upgraded
1985	Flood with debris	20-year	Torrential rain	Raging torrents through Thames. Hospital, shops and homes flooded	Channel work upgraded
1988	Cyclone Bola	~5-year	Heavy rain		Thames missed the worst of the cyclone
2002	The weather bomb	~100-year	Exceptional rainfall	Highest flows, but torrent "controlled"	Channel repaired By a simple accident of chance, no large debris avalanches were triggered in the upper catchments
Missing for a town with ~140-years' of history	Floods with debris	**>100-year**	Torrential rain	No warning as thousands of tons of debris carried by the torrents block channels which overflow and flood the town	Implies that the return periods of some of the above events may be underestimated
Yet to come	Debris with flood	~500-1000 years	Exceptionally torrential rain, perhaps ~3 mm/min sustained for 15 to 30 minutes, probably following shortly after a wet period of exceptional duration.	Widespread flooding. Metres-high wall of mud, rocks and debris races into the Thames Hospital grounds. Homes and businesses destroyed. Debris flows could pour into Thames from any or all of the catchments above the town. Thames in not likely to be the only community hit by the storm.	The current lined channel of Karaka Stream can carry the ~100-year floodwater, but only if there is no debris with it. The return period of debris volumes exceeding the upstream sediment-trap capacity is unknown, but is unlikely to be more than 100-yr.

* An inferred likely course of events in an *ad hoc* world.
** Description as given in historical record unless magnitude specified.

3.0 QUANTITY OF SOLID MATERIAL AND DEBRIS LIKELY TO BE DELIVERED FROM KARAKA CATCHMENT

We can only crudely estimate the volume of solid material likely to be carried from the Upper catchment of Karaka Stream in a debris flow, but of course it is a variable, dependent in part on the magnitude of the triggering event, and in part on the sediment available to be entrained in the passing flow. A method of debris-flow-magnitude estimation that is widely used internationally for engineering design is to estimate the maximum possible size of debris flow from the volume of sediment stored in the channel, and available to be mobilised in bulking up the debris flow as it traverses the channel. This method unfortunately is not useful for Karaka Stream for two reasons. First, the stream channel currently appears to be depleted of sediment (much bedrock is exposed in the stream bed – see Figures 1.3.5 and 2.9.1), and this appears to be an abnormal state. Second, much of the catchment is underlain by hydrothermally altered rocks that are relatively easily eroded from the slopes, and so although the current channel is short on sediment, the hillslopes can readily resupply it in any storm large enough to trigger a few debris avalanches.

It is well established that in any sediment-producing storm, most of the sediment comes from a few very large sources. This makes it exceptionally difficult to reliably estimate the likely quantity of sediment to be mobilised in any one storm.

The current “depleted” sediment storage does mean that the probability of smaller debris flows reaching the fan head is lower now than it has been in the recent past, and it also means that were a huge debris flow to occur tomorrow, it would not be as large now as if it had occurred some decades ago when there was more in-channel sediment available to bulk it up. Unfortunately, it does not mean that huge debris flows can not occur, and much of the available in-channel sediment is in the form of giant boulders (Figure 1.3.5), that once mobilised will be very mobile in the hard, bedrock channel, and so a debris flow now may travel further and faster and be more destructive, than if there had been more finer sediment.

We would expect that a debris flow reaching onto the fan head would have a total volume of solid material (including organic debris) in the hundreds of thousands of cubic metres, with few if any exceeding a million cubic metres; that is, the expected range is 10^5–10^6 m^3. More than half of the material is expected to be sand and silt, and about half will be carried in the debris flood beyond the limits of the debris flow and spread through the central business district, and into the sea. Ten to twenty such debris flows could have built the Karaka Stream fan at Thames in the last 7000 years, further supporting our estimate that the recurrence interval of major debris flows reaching the fan is in the midrange of 100–1000 years.

Each debris flow will contain abundant boulders of dense, hard andesite with a few to more than 3 metres in diameter (~50 Tonnes). The debris could arrive at the fan head at speeds of 25–50 km/hr, faster than people can run, but would slow quickly when unconfined and on the lower fan gradients (and especially in the flat area between the hospital water tanks and the hospital buildings).

4.0 LIKELY RESPONSE TO FUTURE HYDROLOGICAL EVENTS

4.1 In the immediate term

As mentioned above, the channel appears to be substantially depleted of fine sediment, with much of the channel lying directly on hard bedrock. This has the effect of raising the threshold at which storms can trigger large debris flow that could reach the fan head, so for the moment, a more “exceptional” storm is needed to get a large debris flow going than might normally be the case.

4.2 In the short term (up to ten years)

Large debris flows are unlikely but possible. Although there is little sediment available in the channel to bulk up any debris flow, there still is enough for a dangerously major debris flow, should the appropriate meteorological circumstances arise. The currently depleted sediment store could be replenished in a single event, or in a sequence of storms. There is little point in monitoring the in-channel sediment storage on a regular basis because the event(s) that refill it will be obvious, and associated with major flooding and channel maintenance at Thames. When the store is replaced, an exceptional storm will still be needed to mobilize the store. Whether the store comes and goes over time periods as short as ten years is unknown to us. There is not likely to be any regularity in its comings and goings. There is no obvious reason why it is missing at present, other than the fact that no recent storm has triggered the formation of a large erosion scar. This is a quirk of probability and not a matter of good land management.

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

Over the next 1000 years, the presently depleted in-channel sediment stores will be replaced many times and we would expect one or two debris flows to spread onto the top of the fan at Thames. We saw the deposit of a past debris flow several metres thick in the banks of Karaka Stream at the fan head. Based on its degree of weathering since deposition, it is quite a few hundreds of years old, but probably less than 1000 years old. We also know that it is only the latest of a number of very large debris flows that have flowed out onto the fan, a process that has been going on for many hundreds of thousands of years in the evolution of the ancient volcano; it is not about to cease.

5.0 AREAS AT RISK FROM DEBRIS FLOWS AND DEBRIS FLOODS FROM KARAKA STREAM

The presence of the hospital complex near the apex of the Karaka Stream fan conveniently limits the area at risk from debris-flow impact to that area upstream of the hospital (Figure 5.0.1), but it does little to limit the areas at risk from flooding. The hospital building complex possibly is the only building complex in Thames of a scale able to withstand debris-flow impact, particularly so because it has an upstream flat area (from the water tanks to the car park) that will reduce the impact velocity of boulders against necessarily strong structures. The hospital's emergency water supply unfortunately is particularly vulnerable to debris flows. Indeed, it probably is vulnerable to anything that overwhelms the existing Karaka Stream flood-mitigating works (which are designed for the 1/60 AEP event).

Figure 5.0.1 Aerial photograph of the Karaka Stream fan head showing areas at risk from a debris flow of about 1/1000 annual exceedence probability (AEP). This figure does not show the areas downstream at risk from the consequent debris flood and floodwater inundation. The boundaries are only precisely definable at the hospital, because they are defined by existing substantial buildings. Limits at higher probabilities (debris flows occurring more frequently) lie **at,** or upstream of, the hospital, but are not otherwise definable on existing data. Also, because of the existing large buildings, the limits at lower probabilities, at least to below 1/2500 AEP, remain essentially the same, although the deposits would be deeper because of the greater volumes.

Image sourced from Terralink International Ltd 2002.

Figure 5.0.2 Aerial photograph of the Karaka Stream fan head showing areas at risk from a debris flow of about 1/1000 annual exceedence probability (AEP) after construction of the proposed new hospital wing. This figure does not show the areas downstream at risk from the consequent debris flood and floodwater inundation. The boundaries are only precisely definable where they might be defined by large bunds (not currently in place) or by valley walls. Limits at higher probabilities (debris flows occurring more frequently) lie at, or upstream of, the hospital, but are not otherwise definable on existing data. Also shown are recommended options for short evacuation routes if residents are warned of an impending debris flow – see section 6.1.

Image sourced from Terralink International Ltd 2002.

Thames Hospital has been used in the past as an emergency shelter although it has lost serviceability in at least one historical extreme event. If it were to continue to be used for this purpose, the complex ought to be protected to withstand much the worst that its Thames' site can experience. This probably is a debris flow from Karaka Stream, the like of which Thames has yet to experience. In any event, the 54-bed new wing should be of a standard that it will not collapse or endanger its occupants in events as rare as 1/1000 AEP. It is technically feasible and practical to construct a large building that can withstand a Karaka Stream debris flow and not endanger lives within it through collapse, or loss of ability to evacuate after a disaster. This construction might include an energy-absorbing buffer of compacted soil to the height of the expected debris flow. Protecting the proposed wing, and consequently the entire hospital complex, has an advantage to Thames — it eliminates much of the debris-flow hazard lower on the fan, but it does not change the hazard upstream.

The broad areas at risk from future flooding are relatively easily delineated for much of Thames because they will not differ from those areas affected in past floods, and are best determined from detailed historical records (hence they are not shown on Figures 5.0.1 or 5.0.2). The existing excellent flood mitigation works unfortunately do not alter the areas at risk; they only alter the threshold at which damage occurs. In the debris-flow scenario large enough to bring a debris flow out onto the fan at Thames, the floodwater is accompanied by a huge outpouring of sediment more than capable of overwhelming the capacity of the lined channel of Karaka Stream through Thames. Once the sediment-storage capacity of the existing scheme is overwhelmed, it is as if there were no flood mitigation. The upper hospital car park and the proposed new hospital wing can be designed to safely stop a large debris flow, but they are not easily designed (and should not be designed) to stop the debris flood, or floodwater that will flow beyond the debris-flow limits (though they will, and should control the initial path, Figure 5.0.2).

Debris floods in Thames from Karaka Stream have a historical annual occurrence probability of 1/35. Substantial mitigation work has decreased this probability, but not greatly so. Karaka Stream appears to have carried a ~1/100 AEP flood in 2002, but this occurred without large amounts of debris, and the outcome of the 2002 event in Thames may have been very different if large debris avalanches had been triggered in the upper catchment. Hospital serviceability currently is vulnerable to any event of annual probability greater than about 1/60 (which exceeds currently recommended standards of serviceability – 1/25 AEP – for the proposed use of the new wing, but not for use as emergency shelter from an impending event – for which the recommended standard is 1/500 AEP). Such events (debris floods) are not likely to be structurally damaging to any of the larger buildings, but they may disrupt the emergency water supply.

6.0 OPTIONS TO MITIGATE RISK AND MINIMISE THE AREA AFFECTED BY FUTURE DEBRIS FLOWS

All information that we have points to debris flows from Karaka Stream (and other streams) being rare, but potentially extremely damaging events at Thames. No debris flows have entered the town since its founding in 1867, but the downstream associated debris floods have entered the town at least four times. That is, the probability of debris flows in Karaka Stream is something like once in 35 years or so (1/35 AEP), but the probability of debris flows large enough (or larger) to reach the fan head (hospital area) is very much less than once-in-100-years (1/100 AEP), and probably is as low as once-in-500 years (1/500 AEP) or lower. It is, however, probably higher (more likely) than 1/1000 AEP, and certainly much higher than 1/2500 AEP. Once-in-35-years is an unusually high probability for serious flood inundation, and when the added danger of the debris (both coarse sediment and organic 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 acknowledged to be unacceptable for dwellings.

Existing work at Karaka Stream to mitigate the debris component – two debris fences and a small sediment-trapping basin – reduce the risk, but they are intended only to reduce the risk to once in 60 years, notwithstanding that they have coped with a once-in-100-year event on one occasion when there was only limited debris entrained in the floodwater. The debris fences and trapping basin have very limited capacity that is easily exceeded. When they are exceeded, the existing channelled section of Karaka Stream is easily overwhelmed. Nominally the engineering work is intended to provide safe passage for floodwater to an annual probability of 1/60. Events which exceed this capacity by a small amount are not likely to be structurally damaging. There is an issue, however, with events such as debris flows reaching the fan head, for these will greatly exceed the existing sediment-storage capacity. The flow constrictions of the debris fence above the Irishtown bridge, and indeed the bridge itself, ensure that a debris flow that passes this point will have choked the channel and will flow over the fan head, currently the site of a number of homes. It is not possible to prove with available data that such events are likely to happen significantly more frequently that once in 500 years or so, and so, while the danger should be noted for the homes, there may not be a legal requirement to take any other action with respect to the dwellings, and future uses of this residential land. Society, however, has different expectations for some other types of structures and land uses where many people might be involved, particularly if the people are particularly vulnerable members of our society (children, people in care or custody), or if many people would be dependent upon their function in the aftermath of a disaster (police and fire stations and associated emergency-service facilities, and places designated as places to shelter in during emergencies).

In an ideal world, one would not build a town on a debris-flow fan, and one would not knowingly put a hospital on the apex of one. But Thames is built on several debris flow fans, and Thames Hospital is on the apex of the debris-flow fan of Karaka Stream. The flood and debris-flow risk to the proposed new hospital wing could be avoided by building the wing elsewhere. This would leave the rest of the hospital complex exposed to an undesirable debris-flow risk. The existing buildings too could be replaced at a new location, which would leave the Thames Central Business District exposed to a far greater hazard than at present, because removal of the hospital complex would remove the barriers that presently ensure that debris flows will stop there. Were the hospital ever to be removed, it would fall to other agencies to consider alternative protection, and it would likely be to a lesser degree. Note that the downslope debris-flow protection provided by the hospital is purely accidental; although it can be viewed in hindsight as very convenient for others, there is no obligation on any agency to maintain it for that purpose.

Large 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 when such mitigation work is undertaken. For example, a debris-detention basin might be designed to protect $50 million in assets from debris flows of up to 500-year return period. This might be such a level of protection that the community becomes oblivious to the hazard and attracted into the area. By the time an even rarer, and larger debris flow comes along, the damage to protected assets may total $500 million, whereas the damage might have been only $50 million, or less, in the same event if no protection had been provided.

6.1 Regional and local warning systems

It may be that the more practical mitigation measure for the residential areas of the fan is to implement a local warning system with evacuation to save lives, while leaving the properties at risk, and the asset value protected by insurance.

Neither point rainfall measurements nor stream flows provide adequate bases for warning of an impending debris flow at Thames. Most storms with a potential to trigger debris flows are localised convective cells, moving in some broader weather system. They can approach Karaka Stream, or any of the other streams from almost any direction, and need not pass directly over any 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 are 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 have been financed principally to provide warning to aviation of severe weather, and have not been used in the past to warn the public in New Zealand, because of technical limitations. The New Zealand weather radar system currently is being upgraded (December 2005 and January 2006) to give better capacity to warn of the evolution of severe weather. The Thames area is usefully served by the Auckland weather radar. It has dedicated staff, and operates with 24-hour, 7-days-per-week capability. The upgraded Auckland weather radar will scan the sky in the vicinity of Thames every 7.5 minutes, and so will monitor the evolution of severe weather with that resolution. This might realistically give about 10-minutes warning time for evacuation of areas at risk if it is coupled with a forward model of the evolving weather. A radar-based warning system is regional in extent, but it requires an effective 24/7 local means of promulgating any warning to specific residences likely to be affected along a projected storm path.

At a local level, as a result of debris-flow research conducted by the US Geological Survey, debris flows in motion can be detected through high-frequency (sonic range) ground vibration. This equipment is commercially available. Installed about a kilometre above the fan head, an automated system could give several minutes warning of an actual debris flow in progress, and could allow evacuation of vulnerable at-risk areas at the fan head around the Irishtown bridge and upper hospital car park if the local residents can tolerate some false alarms. A similar installation may apply at Hape Stream, but would not be useful for the smaller catchments (where the vulnerable homes are within the basins and not out on a fan).

For a warning to be effective, affected residents need to know instinctively what to do when they are warned. Simple evacuation plans are easily taught and remembered. They are used internationally for wild fires and tornados and save lives. It should be noted that at the time any alarm system sounded, there would be a major electrical storm in progress in the hills, and few people would be unaware that the alarm related to the storm (though they may be reluctant to venture outdoors).

6.2 Mitigation options at Karaka Stream

Karaka Stream has existing measures designed for a 1-in-60-year event, but has many other areas which appear to be suitable for further retention of boulders and logs. Additional structures would need to be designed for much larger events. Structures, such as is illustrated in Figure 6.0.1 are suitable. Given that the width of the Karaka Stream channel has been cut by very large debris flows, no one structure is likely to sufficient to stop everything in one debris flow, and a chain of structures is likely to be more practical. Because of the nature of the catchment (limited storage capacity in the channel, and effectively unlimited supply on the slopes), and the nature of the prime asset on the fan (Thames Hospital), we must consider the rare exceptional events that will overwhelm the capacity of even a chain of structures – even if we decide not to do anything about them.

Even if in-channel, debris-retention structures are used, the upper hospital car park, and grassed area up to the hospital emergency water storage tanks (hereafter referred to collectively as the *upper car park*) also is a default retention structure, the last in a chain if debris flows were to reach the fan head. Were a future debris flow to spill from this currently unintentional detention basin, its path would be unconstrained. There is scope to constrain it. If the hospital complex is to remain in its present site, it will have to safely withstand whatever issues from the mouth of the gorge (or it will not remain on the site), whether this be a debris flow with boulders, or a hyperconcentrated flow with the boulders strained out by upstream structures. The design of a channel capable of safely passing a debris flow as large as could occur in Karaka Stream is not practical; such a channel would look very similar to the deep gorge of the kilometre of channel upstream of the Irishtown bridge and have a similar gradient, unavailable beyond the hospital area. Such a deep, steep-sided channel itself would be a constant danger to life, whereas dangerous debris flows occur only every few hundred years or so.

Figure 6.0.1 A debris-retention outflow structure in a sediment-storage basin protecting a northern suburb of Vancouver, Canada. This structure is intended to safely stop events occurring about once in 500 years. To retain this capacity, the basin must be maintained relatively free of debris, and would be cleared after each significant sedimentation event even when these were not debris flows. There is a service road to access the basin for sediment removal.

It probably is impractical to design a lined channel that could not be choked with sediment during a debris flood, because there is insufficient gradient on the fan. Hence there is a need to ensure that whatever water and debris reaches the lower end of the car park can pass by the hospital-building complex, without unduly endangering life safety in the hospital buildings. Here, safety is with respect to the hospital and its occupants, and not to the adjacent areas of Thames. In such an exceptionally rare event, the hospital should easily survive as a haven in the midst of chaos and catastrophe, even if it is isolated for a brief period.

Karaka Stream is not the only Thames stream with a debris-flow hazard, but it may be the only stream where debris flows directly threaten such a significant local asset (the hospital complex) in constant 24/7 use, and for which rapid evacuation is impractical. Structures such as is illustrated in Figure 6.0.1 could be built in the channel of Hape Stream, but would not be necessary unless there were another large care facility or a school at risk on its fan.

Fire and Police Stations, and garages for Emergency vehicles are somewhat more easily relocated to areas that meet the appropriate very high serviceability and life-safety requirements, should any such buildings be at risk.

7.0 CONCLUSIONS

- The town of Thames has developed on a series of large debris-flow fans, but it has yet to experience a debris flow entering it since its founding in 1867.
- Debris flows have occurred in Karaka Stream at least four times in the last 138 years. The sediment and organic debris washed from them have made the associated downstream flooding in Thames worse than if there had been only the floodwater.
- The return period of such debris floods in Thames was about 35 years. The return period has been increased by mitigation work, but not greatly so.
- In the last 7000 years, many (~10–20) large debris flows (~100,000–1,000,000 m^3) have reached the area now occupied by Thames Hospital. The return period of large debris flows capable of reaching into Thames is much greater than 100 years, but less than 1000 years.
- Existing mitigation work on Karaka Stream can safely carry water flows of at least 100-year return period when there is little sediment, but it is not able to cope with large sediment influxes (~100,000 m^3 and greater) likely to be associated with future debris flows, whether or not a debris flow reaches the fan head at the upper Thames Hospital car park.
- The effect of a major debris flow on the Thames Hospital complex currently is partly mitigated by the upper car park. The effect of the car park could be exploited to ensure that the building complex survives any future debris flow without endangering patients or staff. This could be achieved by designing the car park as a non-water retaining, debris storage area, and ensuring that sediment-laden water can safely pass around the building complex.
- The hospital emergency water supply is stored on the debris-flow fan head and is vulnerable to any future large debris flow that takes out its source or storage tanks.
- Safety requirements for the hospital should exceed those for the remainder of the town. Providing measures to ensure life-safety at the hospital during a major debris flow would eliminate the debris-flow danger downstream of the hospital and not make the flooding and debris-flood hazards worse.
- If people downslope of the hospital complex desire greater protection of them and their assets from flooding, it is most easily achieved by trapping more sediment upstream of the hospital, and even upstream of the fan head, but protection from events much above 100-year return period may be impractical, and some form of warning system, with time to evacuate, should be considered.
- Improvements to New Zealand's weather radar system currently being implemented by the New Zealand Meteorological Service should enable Severe Weather warnings to be issued within ~10 minutes, as severe weather evolves and potentially before a debris flow is initiated. Once initiated, debris flows can be detected through sonic-range ground vibrations using currently available technology. Automated detection could give a few minutes' warning, enough to evacuate the immediate impact area above and including the hospital car park. There is no possibility of having enough warning to evacuate the hospital complex.
- The currently proposed site for the new wing of the Thames hospital is suitable provided the building is well constructed and protected from direct debris-flow impact.

8.0 RECOMMENDATIONS

- The Thames community considers the implications of future major flooding with debris in the central business district and elsewhere, and determines agreed levels of affordable protection that they may not currently have. Achieving this level may require additional sediment traps in Karaka Stream and elsewhere.
- The Thames community makes use of the future capacity of the New Zealand Meteorological Service to provide effective severe-weather warnings.
- The Thames community considers the practicality of implementing debris-flow detection systems on Karaka and Hape Streams
- The Thames Hospital management notes the vulnerability of the hospital's current emergency water supply in extreme floods and debris flows in Karaka Stream.
- The area in the vicinity of hospital upper car park be re-fashioned to function additionally as an effective debris-flow storage basin, with a large, high bund against the new wing. The intention of such bund is to cushion the new building against a direct hit by a debris flow and to safely deflect debris-laden floodwater (and any additional debris-flow volume) around the entire hospital-building complex.

9.0 ACKNOWLEDGMENTS

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[viii] Appendix 1 "History of flood events on the Thames coast" in "Reducing the flood risk"