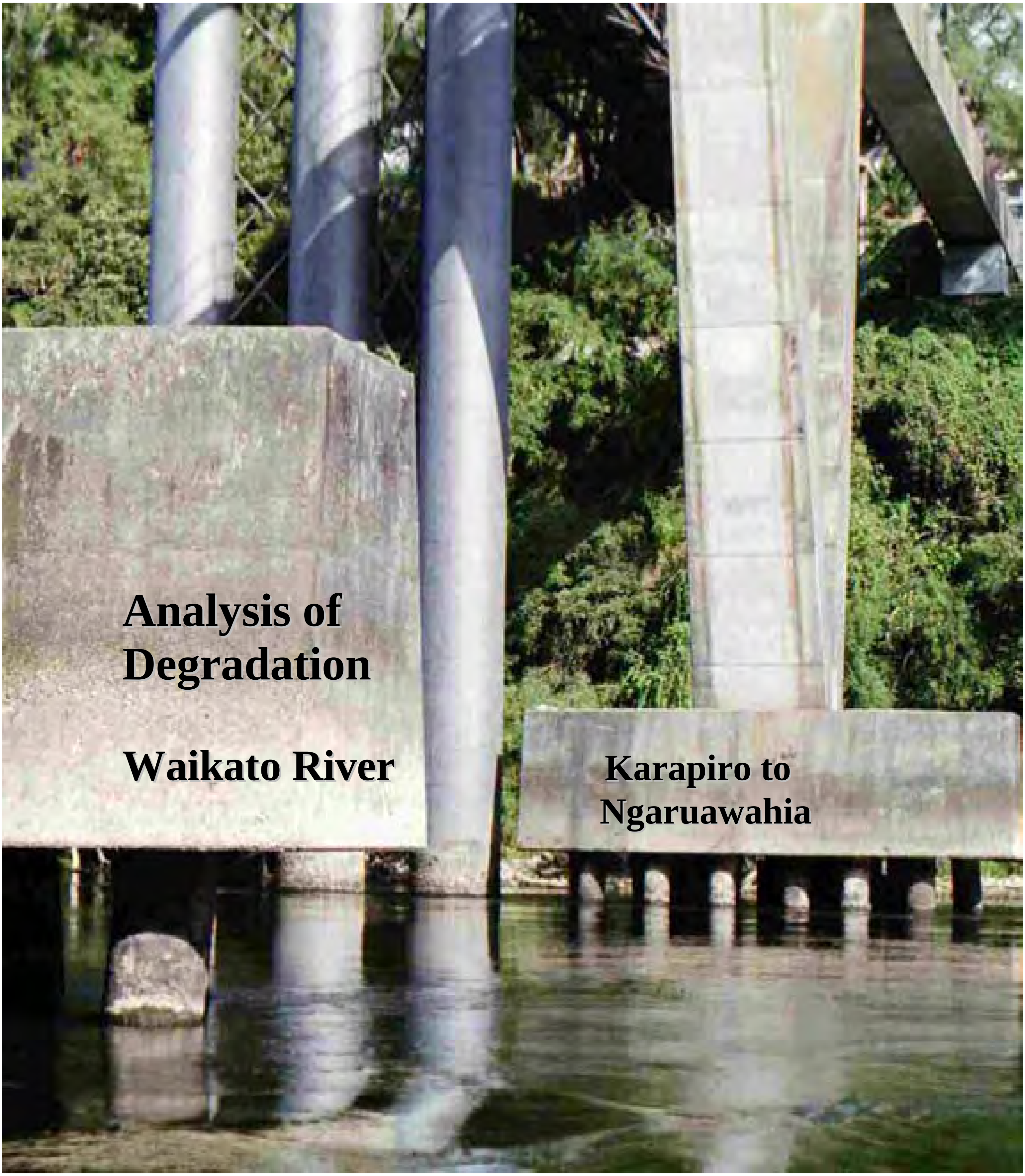

Analysis of Degradation

Waikato River

Karapiro to Ngaruawahia

Environment Waikato
P.O. Box 4010, Hamilton East,
New Zealand.

August 2005

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Degradation.
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Karapiro to Ngaruawahia.

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For Environment Waikato
P.O. Box 4010, Hamilton East
August 2005

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1. Summary

Under Stage II of the Middle Waikato River Bed Degradation Project, mechanisms affecting bed degradation were investigated by studies: (a) to find the location of any hard sills in the bed, (b) to seek evidence of widening of the river through bank erosion, (c) to measure the effects of hydroelectric flow ramping on sediment movement and (d) to sample the composition of river bed substrates. These studies showed that:

(a) There are several high sills in the bed and 59 sites of potential hard strata (according to a seismic survey between Horotiu and Narrows Bridge).

(b) There is evidence of local widening at a number of locations but overall the river is narrowing. Degradation is greatest at narrow sections of the river. The river morphology is highly dynamic and cyclic with previously widening reaches now narrowing and vice-versa.

(c) Hydro ramping mobilises sediment sizes that would not be expected to move under steady flow conditions but, at the two sites investigated, very rapid ramping moved but did not break a protective surface layer of gravel on the bed.

(d) No hard strata were evident in any boreholes. Recovery rates from the borehole cores were poor and no mapping of underlying strata was possible. The one borehole that intersected a seismically detected hard stratum showed the bed comprised gravel at this location. The boreholes found strata up to 8m below the bed to be predominantly sand, silt and fine gravel which are easily erodable.

The Stage II studies gave no reliable evidence of any features that will prevent continued degradation or reduce its rate. The existence of hardened sills was not verified. Potential hard strata, evident on seismic traces, need to be verified by boreholes. Further boreholes are recommended to investigate the composition of four high sills which could rapidly accelerate the rate of degradation should they be eroded.

Extrapolation of the present degradation rate indicates that, unless constraints are encountered or there is widespread bank collapse, mean bed levels in Hamilton could fall to 1.5 metres below the present position over the next 50 years. Such rampant degradation will eventually lead to bank collapse, undermining of riparian structures and headwards erosion of unprotected tributaries.

On the basis of this information, measures to manage future degradation should not be delayed. Most importantly, calculations of bank stability are essential to identify future hazards and to ascertain when bank collapse will begin to supply sufficient sediment to reduce the present degradation rate. A continuation of the bathymetric surveys and LiDAR monitoring of banks every 5 – 10 years is recommended in order to detect future irregularities. Intensive monitoring of a typical degrading reach would be constructive to establish precisely when episodic bed degradation occurs.

Follow-up Investigations

Additional boreholes were drilled as recommended above and organic material from the bore holes was carbon dated.

The carbon dates and bore logs confirm that the high sills through Hamilton City contain no hard strata but comprise recent, easily eroded alluvium that is unlikely to constrain the present degradation.

Carbon dating of a bed sill 1.5 km upstream of Horotiu Bridge indicated material there to be over 45,000 years old. The presence of such old material overlying probable Hinuera formation indicates that the river bed at this location does not comprise recent alluvial deposits. The silty peat bed material found here is, however, unlikely to offer a barrier that is resistant to degradation.

As a result of the follow-up studies no change in the predicted degradation rate is warranted.

For discussion purposes, the causes of degradation were investigated. The conclusions are that the following factors have contributed to bed degradation (in order of decreasing importance) : hydro dams cutting off sediment supply from upstream, hydro ramping waves increasing the entrainment of bed material, historic mining of river sand, diversion of additional headwaters into the Waikato River by the Tongariro Power scheme, changes in land use in the river's catchment areas and river management practices that have reduced bank erosion.

2. Background

Previous investigations have shown that the average Waikato river bed level is falling at an average rate of around 30 mm/year in the vicinity of Hamilton City. Prior to the 1950's the bed in the Hamilton region was mildly aggrading (Kear et al, 1964; Smart, 2003). The primary cause of degradation over the last half century is that hydro dams trap sediment input from upstream and the underfed river entrains material from its alluvial bed. In the 1960s and 1970s sand and gravel extraction aggravated the degradation. Extrapolation of specific gauge records and bed trend lines point to degradation starting around 1947 and originating in the vicinity of Karapiro Dam (Smart, 2003). Degradation downstream of dams usually diminishes with time and aggregate extraction from Hamilton reaches has now ceased. However, recent surveys show no decrease in the degradation rate.

An indication of the problem is given in Figure 1 which shows changes in mean bed level at a series of cross sections monitored by Environment Waikato. Areas shown in grey have not changed in level since 1973.

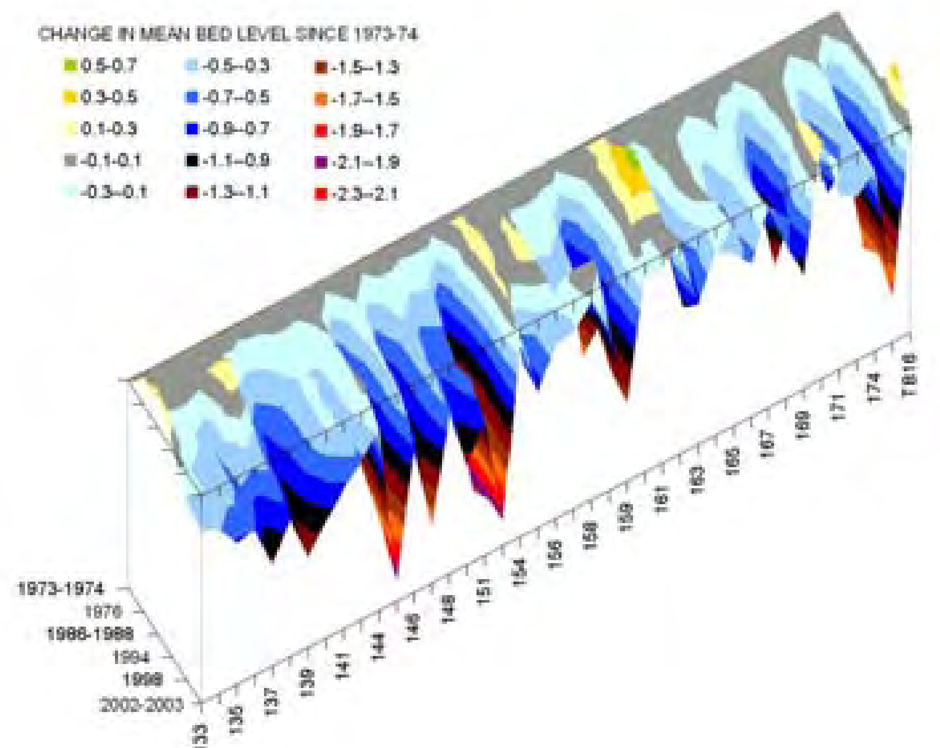

Figure 1 Changes in mean bed level since 1973, shown in metres, from Section 133 (near Ngaruawahia) to Section TB16 (near Karapiro Dam).

At Bridge St in Hamilton, water levels (for a given flow) have not been falling as fast over the years as the mean bed level. The rate of water level fall appears to have decreased in recent years. Possible explanations for the difference between the steady fall in mean bed level and the decreasing rate of fall in water level could be that erosion resistant sills are controlling the water level and/or water velocity is decreasing due to increasing channel roughness or increasing channel width.

Because the unknown potential for future degradation is a matter of concern, further investigations into factors governing the degradation were commissioned. In particular, information was sought on:

- the location of any hard sills in the bed,
- evidence of widening of the river through bank erosion,
- the effects of hydroelectric flow ramping on sediment movement, and
- the composition of river bed substrates.

Investigations of these aspects were carried out by:

- NIWA (2004) "Middle Waikato River Bed Degradation Investigation: Stage II – Bed Survey", Report HAM2004-050,
- EW(2004) "EWDOCS-#923799-v1, Modelling Report",
- ASR (2004) "Middle Waikato River Bed Degradation Investigation", and
- Opus analysed core samples drilled in the river bed (see appendix 2).

This report summarises the findings of these studies and gives additional analysis of some of the data collected. It concentrates only on aspects considered relevant to bed degradation.

Statements in the report that are not referenced are the views of the author.

3. Bed levels and hard sills

The objectives of the NIWA Bed Survey Study were to measure a long profile and carry out seismic tests of the river thalweg between the Narrows Bridge and Horotiu Bridge to identify any high, hard sills and to measure the stratigraphy of the substrate.

The surveys ran into initial technical difficulties but good data were gathered. NIWA found a comparison of elevations from the bathymetric thalweg survey showed good agreement with previous measurements at river cross-sections measured by EW.

The thalweg survey identified many high and low points in the bed that lie between the cross-sections monitored by EW and demonstrates some shortcomings of basing models and conclusions on cross-sections measured hundreds of metres apart. There appear to be humps in the bed not detected by cross-sections (for example, 300 m downstream of cross-section 139, 270 m upstream of section 140 and 110m upstream of section 153A) which may influence cross-section based hydraulic model predictions when taken into consideration.

A graphic picture of variations in bed level is indicated by deviations of the thalweg from its linear trend line as shown on Fig. 2 and Fig. 3.

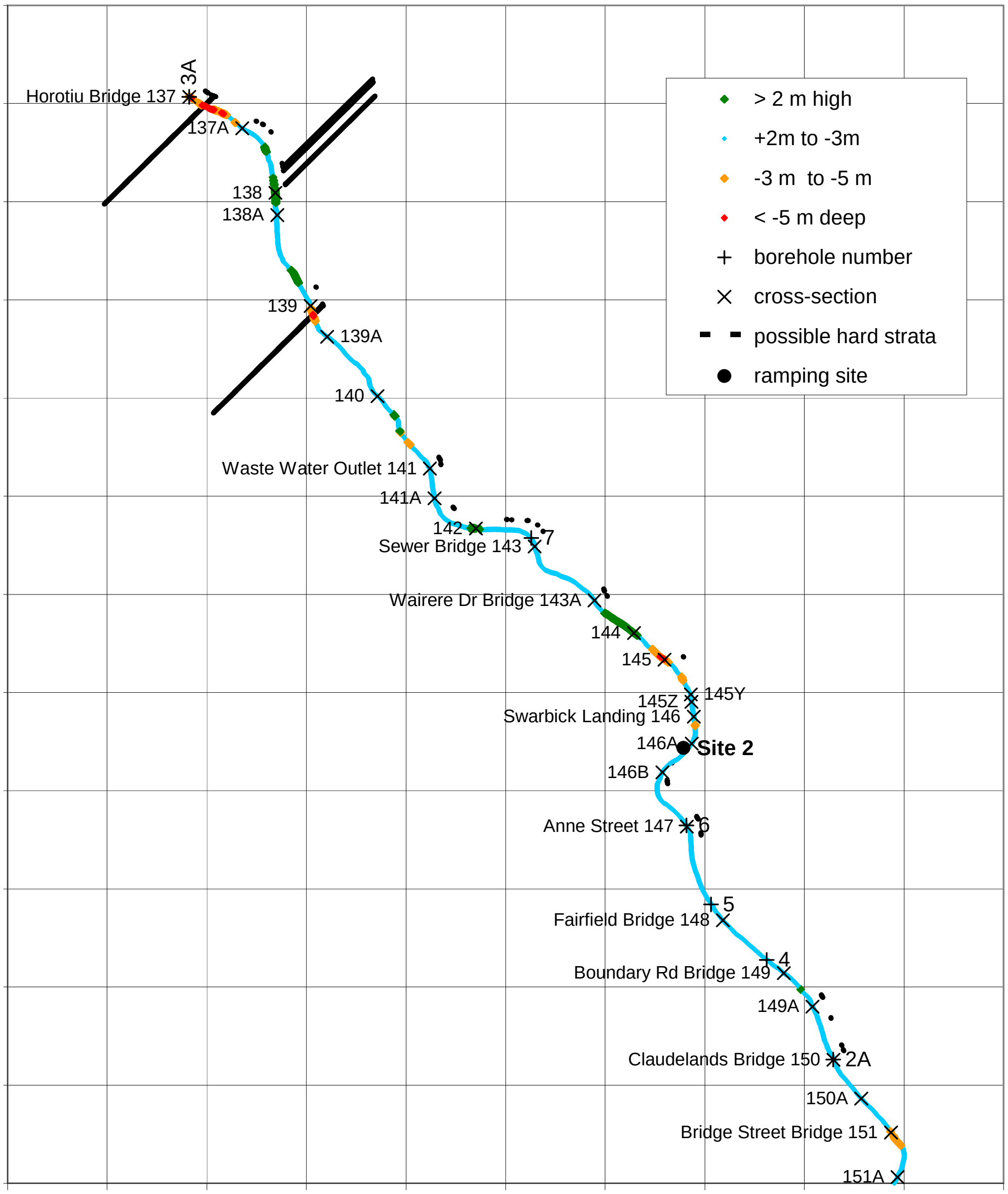

Figure 2 Bed levels of Northern Hamilton reaches, indicated by deviation of the thalweg elevation from its linear trend line. Possible hard strata, cross-sections and borehole measurement locations are shown. Grid size is 1km.

In these figures, dark green points show where the thalweg lies over 2 metres above the trend line. Such high points are potential hard sills in the bed. Black dots alongside the river right bank show where the seismic survey indicated potential hard strata in the bed. Although underlying the river channel, for clarity the potential hard strata points are offset in a NW direction on the figures.

Four locations where high points correspond to potential hard strata are marked on the figures by diagonal lines rising to the right of the river. These are located 1.25 km and 1.43 km upstream of Horotiu Bridge on Fig. 2 and between 0.45 km and 2.53 km downstream of the Narrows Bridge on Fig.3. There are three high areas (shown in green) in the central Hamilton region. These are located halfway between sections 153A and 153Z on Fig. 3, and on Fig. 2 between Boundary Rd Bridge and section 149A and from section 144 downstream. None of these correspond to locations of hard strata indicated by the seismic survey. In Hamilton the thalweg is quite flat from just below Bridge St to the golf course just upstream of Swarbick Landing on Fig. 2. The flat bed could indicate an alluvial substrate with no hard sills.

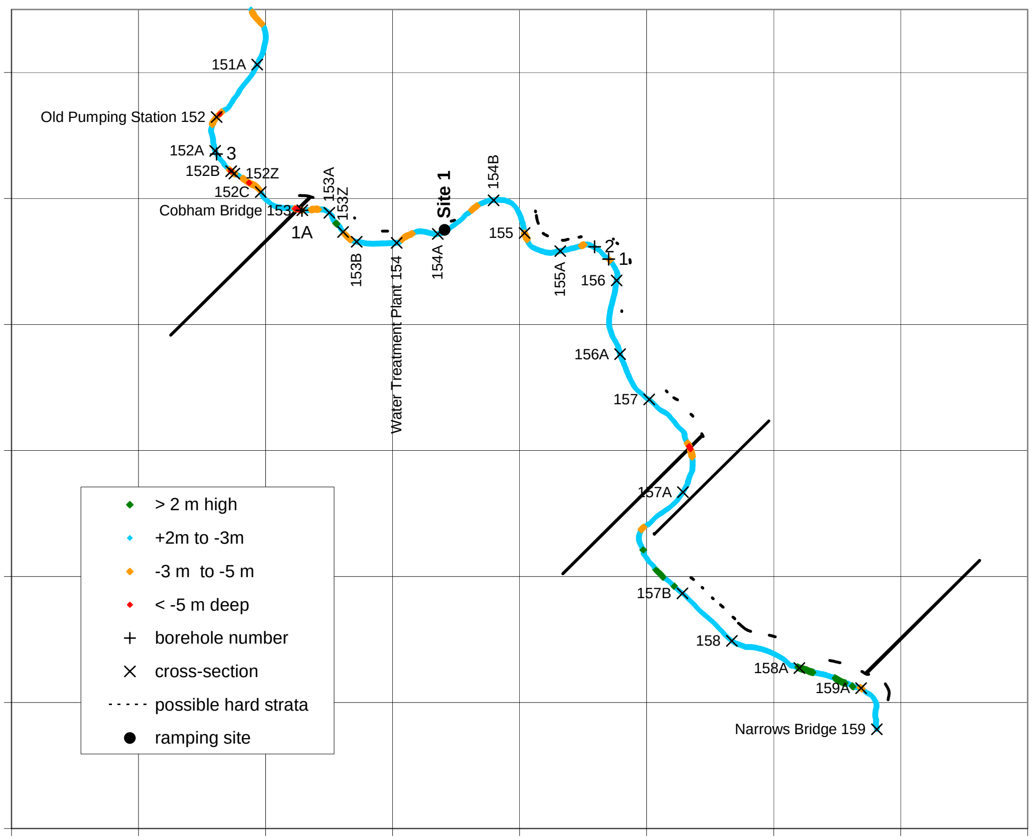

Figure 3 Bed levels of Southern Hamilton reaches, indicated by deviation of the thalweg elevation from its linear trend line. Possible hard strata, cross-sections and borehole measurement locations are shown. Grid size is 1km.

Low points in the thalweg are shown on Fig. 2 and Fig. 3 in orange and very low points are shown in red. Four locations where very low points correspond with indications of potential hard strata are shown by diagonal lines to the left of the river. These are at 180 m upstream of Horotiu Bridge (where the bed is only 0.39 m above sea level datum), 2.77 km upstream of Horotiu Bridge (bed level is 1.01 m above datum), 30 m downstream of Cobham Bridge (bed level is 1.08 m above datum) and around half way between cross sections 157 and 157A north of the city (bed level is 2.52 m above datum). There is a notable low section downstream of the golf course, near section 145 where the bed level falls to 1.43 m above datum and no hard strata were indicated. Low points in a thalweg are typically found on the outside of river bends (see orange and red reaches on Figs 2 and 3). While this explains many of the low points between the Narrows and the Golf Course, downstream of Swarbick Landing there are deep sections in straight reaches.

Several locations of possible hard strata coincided with cross-sections surveyed by EW. These were at sections 141, 143A, 147, 149A, 150, 155, 158. The last four of these have had stable bed levels.

Borehole locations (discussed in section 5) and ramping measurement sites (section 6) are shown on Figs. 2 and 3 with their reference numbers.

In summary, the bed survey revealed higher and lower bed locations than had been detected by previous cross-section surveys. Many potential hard strata were identified. These are referred to in section 5.

4. Degradation and changes in river width

Degradation can produce a situation of critical bank stability that causes a river to switch from deepening to widening. To investigate this possibility, recent changes in river width were studied.

Four sets of surveyed cross sections in the reach from Karapiro to Ngaruawahia were used. Ideally the cross sections in each set should have been surveyed during a short time period in which there were no floods, in order to give a clear snapshot of the river at that time. In reality, the channel surveys took several years to complete. The four “blurred” snapshots are taken to represent conditions in 1973, 1991, 1998 and 2003 (data for these years were actually collected in 1970-1976, 1986-1994, 1998 and 2002-2003 respectively).

For this type of investigation it is necessary to have a reference level at which surface widths are compared. The width at the level of the average annual flood was selected as this is generally considered to be the “channel forming discharge”. A width investigation was commissioned by EW using the Mike 11 hydraulic model and the four sets of measured river cross-sections. The annual average flood was taken as 490 m^3/s input from Karapiro and 350 m^3/s from Whatawhata. The calibrated Manning’s coefficients did not need to be changed for the different time periods indicating that channel roughness can be considered relatively stable over the years. Locations of Hamilton cross-sections where width was calculated are the same as those shown on Fig. 2 and Fig. 3. The widths of the reference flood along the channel are shown in Fig. 4 for the 1973 and 2003 cross-section sets.

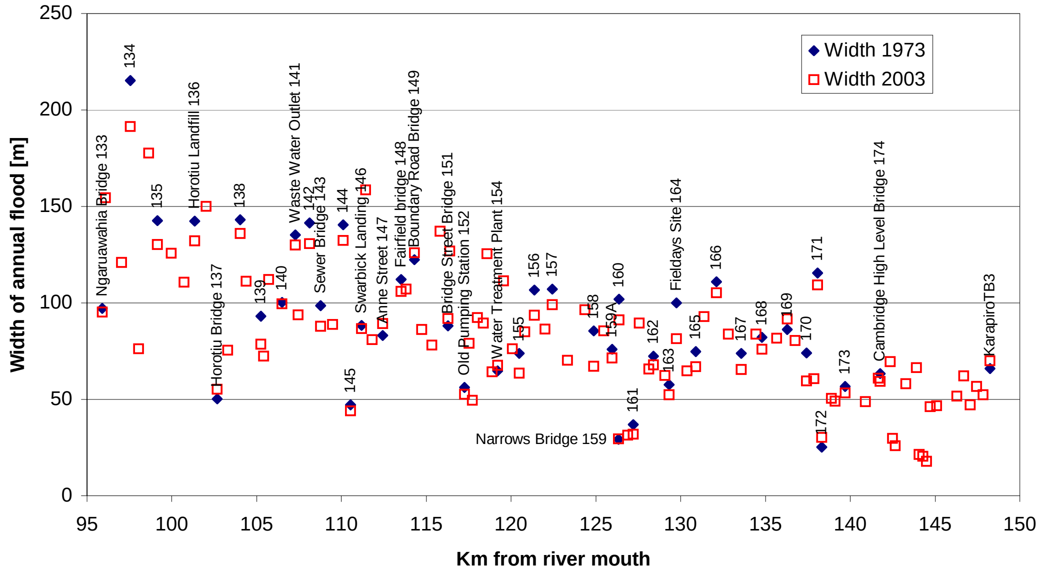

Figure 4 Profile of flood widths from Ngaruawahia to Karapiro in 1973 and 2003.

The flood widths narrow from over 150m near Ngaruawahia to less than 50m near Karapiro. At most sections, the width of the mean annual flood has narrowed over a 30 year period (blue diamonds lie above the red squares on Fig. 4). Summary statistics on annual flood width in the Hamilton region are given in Table 1. The apparent increase in mean width between 1991 and 1998 is mainly because the average width of an additional 25 cross-sections included in the 1998 and 2003 surveys was greater than the average width of the earlier sections.

Table 1 Changes in width of an annual flood at measured sections between Horotiu Landfill and Narrows Bridge.

Survey year reference	Number of sections	Mean width [m]	Minimum width [m]	Maximum width [m]	Std. deviation
1973	23	95.0	29.3	143.2	33.0
1991	25	89.0	28.6	136.5	29.3
1998	50	93.8	42.7	156.6	27.7
2003	50	93.2	29.4	158.6	28.4

The notable widening of the minimum width in 1988 (section 159, Narrows bridge) may be caused by miss-alignment of the cross section or a temporary change in bed levels or a modelling error.

The spatial and temporal distributions of changes in river width during the last 30 years, according to the modelling, are shown in Fig. 5.

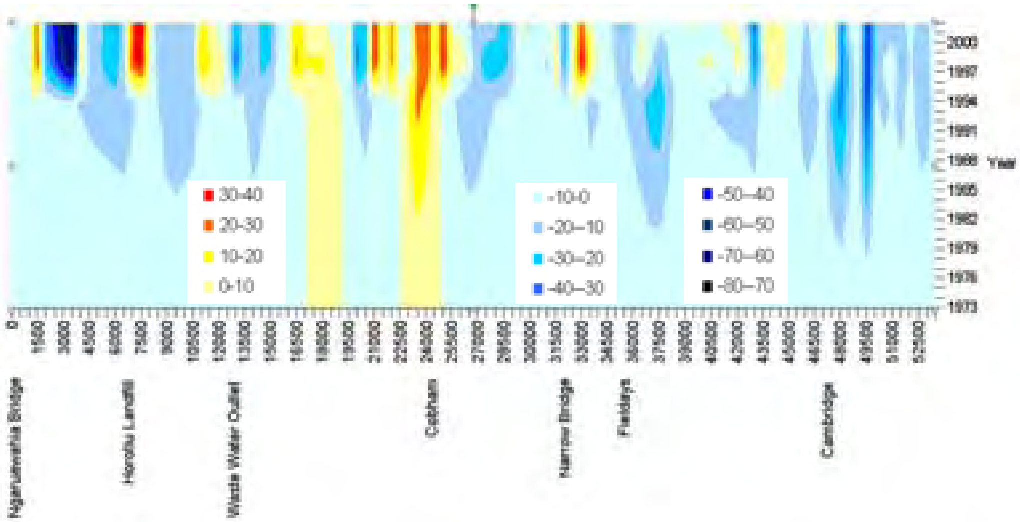

Figure 5. Changes in width of an average annual flood from Ngaruawahia Bridge to Karapiro between 1973 and 2003 (yellow, orange and red indicate widening up to 40 m, darker blue regions show narrowing of up to 80m). Ref. EWDOCS-#923799.

The greatest increases in width occur just upstream of Horotiu Landfill and close to the city centre (from the Water Treatment Plant to Anne Street).

These results must be interpreted with caution because the change in the number of cross-sections effectively means that a different hydraulic model was used to calculate width in 1973 and 1991 from that used in 1998 and 2003. Thus trends between 1973 and 1991 can be compared with trends between 1998 and 2003 but width values from the pre-1998 model cannot be directly compared with values from the 1998 and 2003 model runs.

More details on the changes in river morphology can be gained from investigating inter-relationships between channel width and depth and the rates of change in these parameters. In these analyses, changes in channel mean bed level (MBL) with time and deviation of MBLs from a uniform plane (a fitted trend line) are used as indicators of degradation. At surveyed cross-sections MBLs were calculated by Environment Waikato as the local average-channel-depth below a standard reference level.

Fig 6 shows deviation of the MBL from its trend line and the annual flood reference widths for the 2003 survey. This figure demonstrates that wider cross sections deviate very little from the trend line (reaches of 80 m width or greater are generally within 2m of the trend line). The two widest sections lie downstream of Horotiu.

The deepest reaches (relative to the trend line) are also narrow and lie close to Karapiro Dam (TB section numbers on Fig. 6). The highest reaches (relative to the trend line) have moderate widths and also lie close to Karapiro Dam. It is understood that these very high reaches are situated on bedrock. When these reaches are excluded a clearer pattern is evident as shown in Fig. 7 which shows the same data for reaches between Horotiu Landfill and Narrows Bridge.

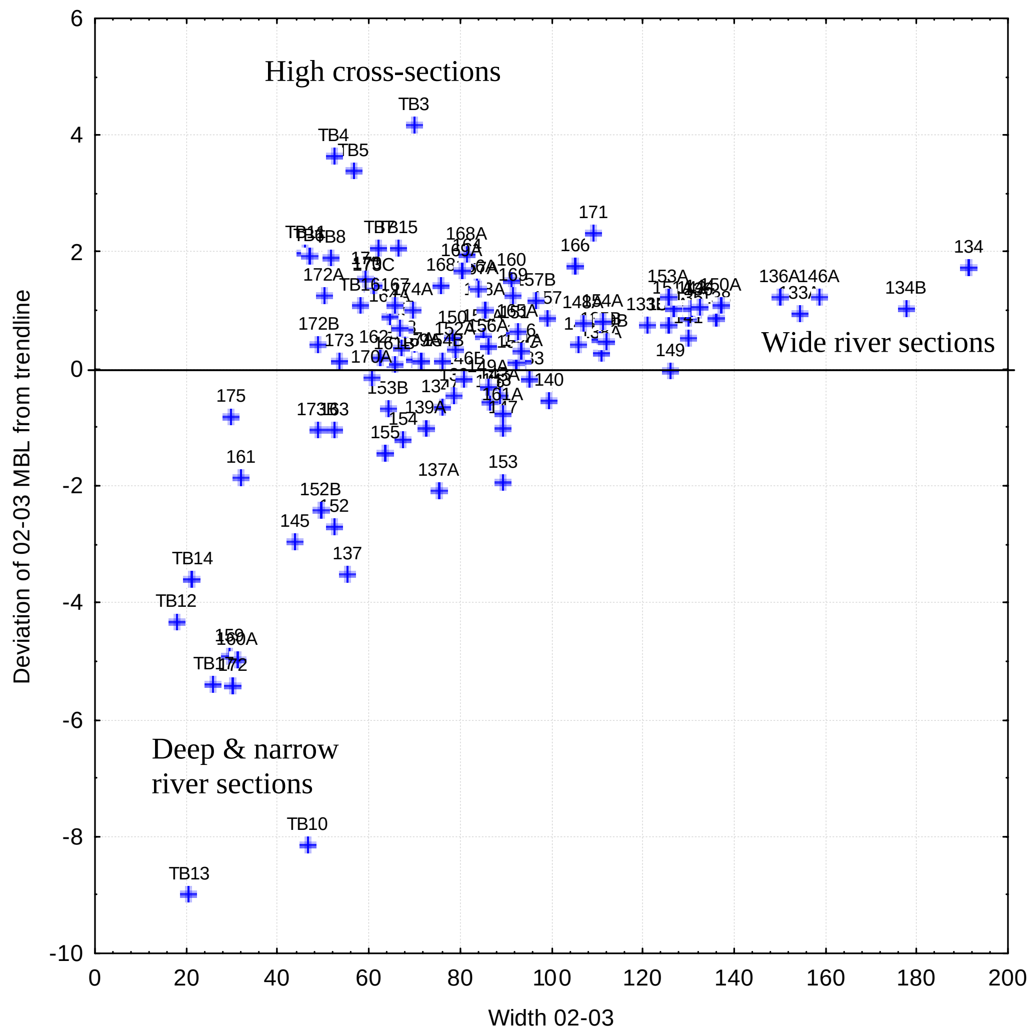

Figure 6 Deviation of Mean Bed Level from its trendline and flood width for the 2003 survey data, Ngaruawahia to Karapiro.

For the Hamilton region, narrower reaches are relatively deeper, and wider reaches are relatively higher than the uniform bed plane. No wide reaches have suffered serious degradation. Narrow reaches correspond to locations where degradation has been most severe. The two deepest measured sections lie at Horotiu Bridge and Narrows Bridge. The thalweg survey (section 3 and Fig. 9) shows that there are other very deep points in the river between these sections.

To investigate evidence of degradation heralding bank erosion, changes in MBL between 1973 and 1998 were compared with changes in flood width between 1998 and 2003. This is shown in Fig. 8 but no trend is evident which could indicate that sections which degraded prior to 1998 then widened post 1998. It is therefore concluded that the modelling reveals no evidence that a general switch from deepening to widening has occurred.

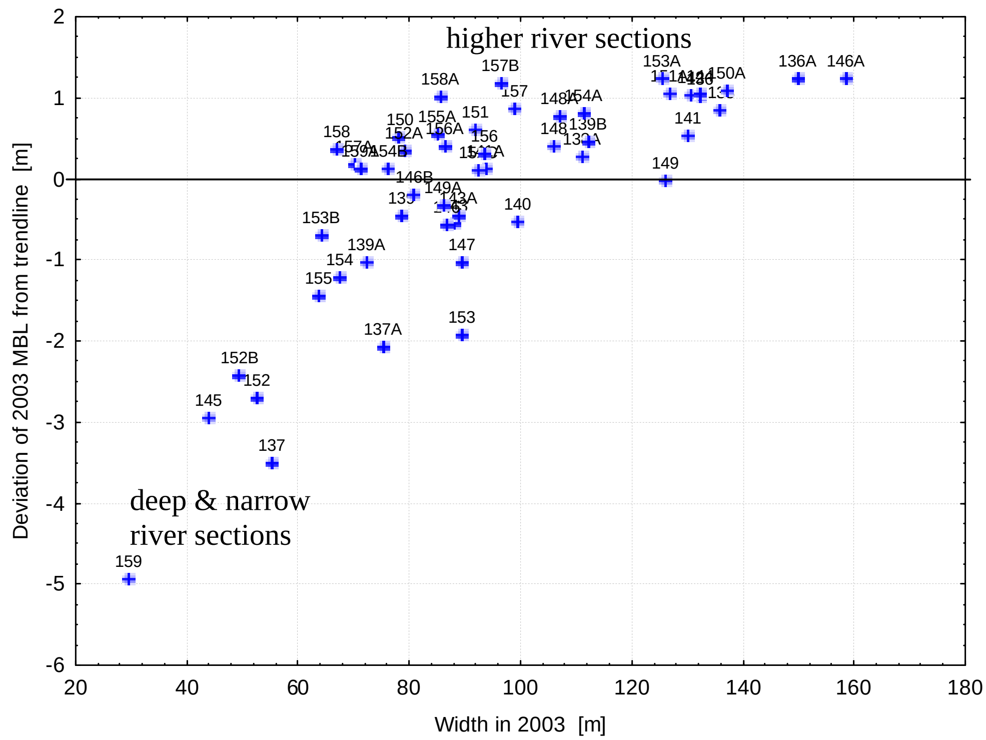

Figure 7 Deviation of mean bed level from its trend line and flood width for the 2003 survey data, Horotiu Landfill to Narrows Bridge cross sections.

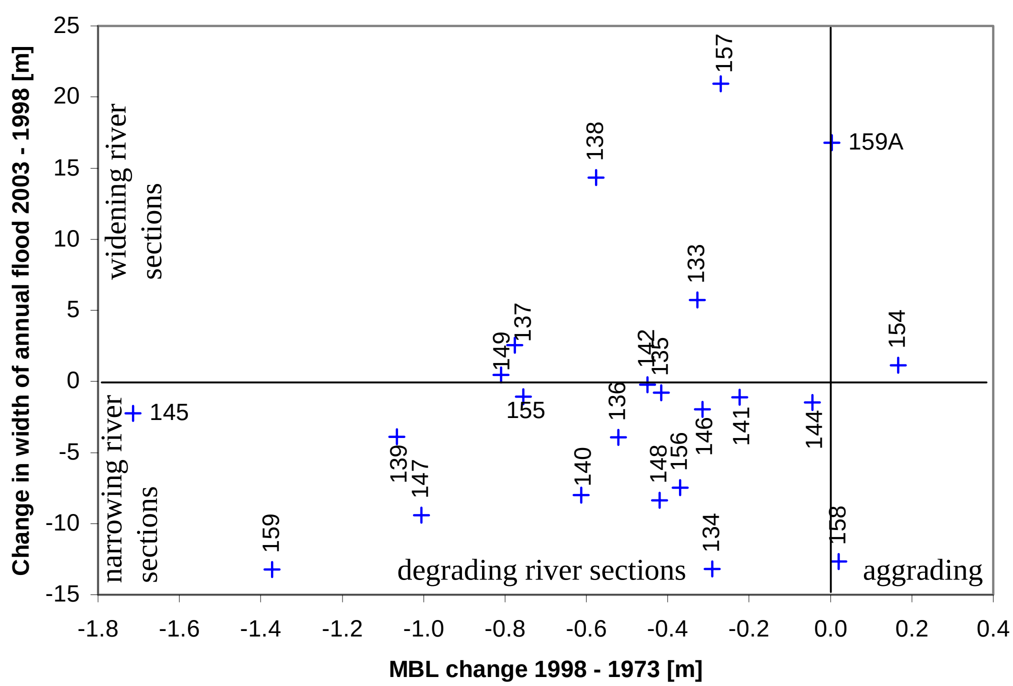

Figure 8 Changes in mean bed level between 1973 and 1998 and changes in annual flood width between 1998 and 2003 for sections between Ngarauwahia and the Narrows.

The question also arises as to whether the wide reaches are stable or whether the wide reaches have previously been narrower reaches.

Fig. 9 shows the changes in width between the 1998 and 2003 surveys compared with the changes in width between the 1973 and 1991 surveys. Negative changes indicate that the channel is narrowing with time.

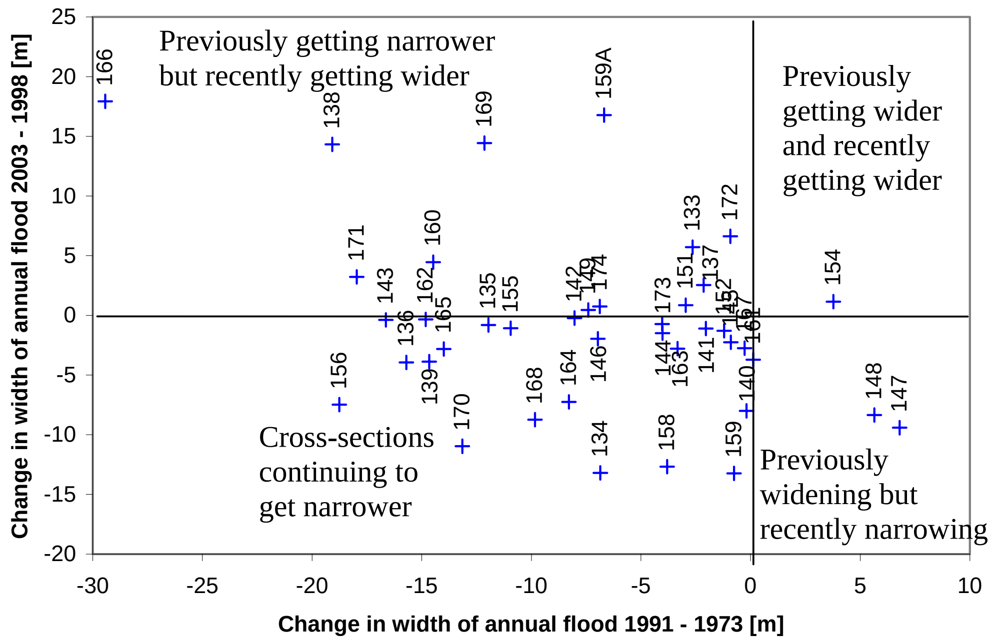

Figure 9 Comparison of recent width changes with past width changes.

This figure clearly indicates the dynamic nature of the degradation process with channels that were narrowing now widening and channels that were widening now narrowing. Within a 1m tolerance, there are no channels which were getting wider in the period prior to 1991 that are continuing to get wider post the 1998 survey.

Because the longitudinal thalweg survey found high and low points along the river bed that were not detected by the river cross-section surveys (which may also have missed some constrictions and bend effects), some questions remain over the accuracy of the modelling results. The findings of this section should therefore be considered along with other evidence.

As continued degradation must eventually lead to bank collapse, a continuation of the bathymetric surveys and LiDAR monitoring of banks every 5 – 10 years is recommended.

5. Bed Substrate Composition

Hard layers corresponding to high points in the bed are important as these could be sills which may help control water level and eventually reduce degradation. The occurrence of any weak layers in the river bed is also of concern because a sudden increase in degradation could occur should these layers be exposed. Earlier studies reveal that peat layers underlie parts of the river (Smart, 2003). It was envisaged that boreholes be drilled at critical locations identified by the seismic survey. Operational constraints necessitated drilling of the boreholes before full results of the bathymetric and seismic survey were available. The locations where the boreholes were drilled are shown on Fig 2, Fig. 3 and Fig. 10. Details of the 90mm diameter core samples are summarised in Fig. 10 and given in detail in Appendix II. Some cores were lost and only boreholes 3 and 7 had an acceptable recovery rate.

The particle size of bed material found in the cores ranged from silt to 90mm stones but the dominant bed material was easily erodable, fine-to-medium sand. The bore hole material was generally loose and non plastic. No hard material (strongly cohesive or indurated) was found in any of the bore hole cores. Only borehole 2A coincided with a seismically identified “possible hard stratum”. The top 3 m of this core was lost but the log of the remainder of the borehole revealed loose, non-cohesive sand and pumice gravel to a depth of 4m followed by 0.5 m of dense, non-plastic fine sand.

Bores 2, 6 and 7 were drilled close to potential hard strata. These cores all contained gravel. Bores 2 and 7 contained indications of a protective gravel layer at the bed surface.

Sills which presently appear to be controlling water levels are marked by arrows A – D on Fig. 10. It is suggested that further boreholes be drilled at these sites to investigate whether hard sills exist. Information from these bores will be invaluable if it becomes necessary to construct bed stabilisation sills at some stage in the future. It is also suggested that a further borehole be drilled at the location of ramping measurement site 2 as discussed in section 6. The recommended locations for supplementary boreholes are given in table 2.

Table 2 Locations at which further boreholes should be drilled

Bore	NZMG Easting	NZMG Northing	R.L of Thalweg.	Distance from EW section	Bed at nearest section
Sill A	2705689	6386077	9.32	25m d/s of section 138	Degrading
Sill B	2706887	6383819	9.88	270m u/s of section 140	Rapid degradation
Sill C	2709207	6381671	10.27	100m d/s of section 144	Slow degradation
Sill D	2712563	6374797	10.73	110m u/s of section 153A	Slow degradation
Site 2	2709786	6380436	not on thalweg	100m u/s of 146A	Degrading

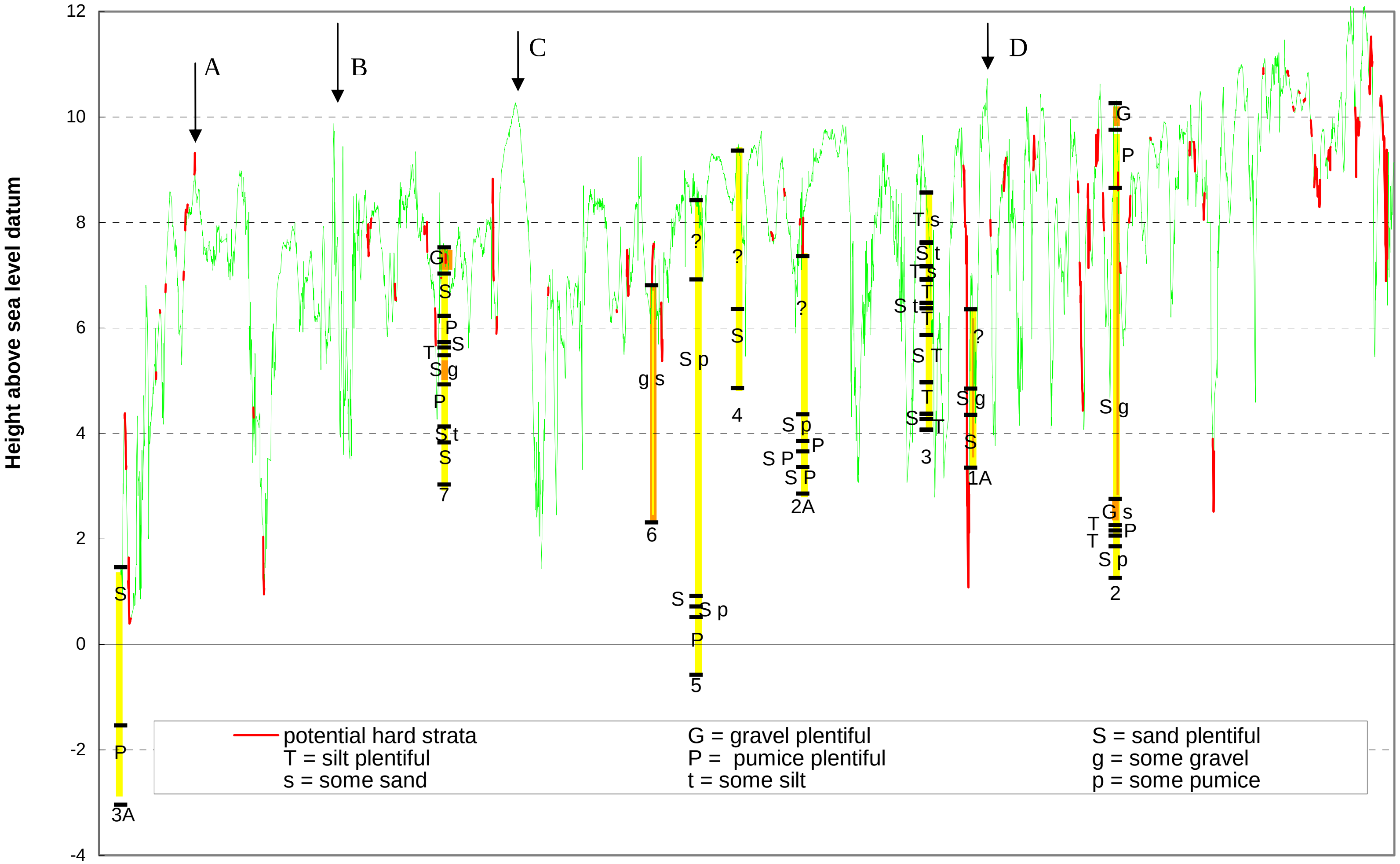

Figure 10 Thalweg (green) between Horotiu and the Narrows showing initial borehole logs relative to potential hard strata (red). Borehole numbers are below the holes. Yellow strata are easily erodable, orange contain gravel. High sills are indicated by arrows.

6. Ramping Effects

The process of releasing storage to generate electricity at times of peak demand creates diurnal surges in river level. This hydro operating technique is known as ramping. Different rates of flow change at Karapiro Hydro Station can cause different ramping waves in the downstream river.

Bed degradation is governed by movement of the riverbed surface material. Bed material transport rate depends on near-bed velocities, flow turbulence and sediment size. The greater the turbulence, the lower the average bed shear velocity required to entrain sediment particles. Because shear velocities and turbulence can be increased by rising flow surges, measurements during ramping rises were necessary to establish whether the present hydro peak load generation rules will accelerate degradation of the river bed.

Crucial questions to be answered are:

- Can ramping cause more transport of river bed material than would occur under natural flow conditions, and
- If ramping causes an increase in bed material movement, is it significant in terms of the annual degradation rate?

While there are many ways that natural rates-of-change in river level could be defined (e.g. should storage effects of upstream dams, etc be considered?), ASR used spectral filtering to effectively remove the diurnal ramping cycle effects which are the subject of this study.

ASR's (2004) analysis of Hamilton recorder water level records from the 1999-2003 period reveals that hydro operations increase the frequency of lower water levels (<12m above datum) and decrease the frequency of moderate water levels (>12m above datum) compared to the "natural" conditions. This effect could help decrease degradation. ASR found the rates of changes in water level (modulated by hydro ramping) were around three times greater than their estimate of natural rates of water level change without ramping (probability distribution shows $\sigma_r = 3\ \sigma_n$). This effect could potentially increase degradation.

Comprehensive measurements of hydraulic and sediment parameters during ramping were carried out by ASR Ltd at the end of April, 2004 in a straight section of river near Hamilton Gardens (Site 1) and at the end of May, 2004 in an expanding reach of river near the Golf Course (Site 2).

Four flow conditions were investigated, two at Site 1 and two at Site 2.

Site 1 measurements were made:

(a) during a very steep section of a moderate amplitude ramping wave, and

(b) at a steady, constant water depth of 2.78m at the measured location (river stage was 12.75m above datum at the Hamilton recorder).

Site 2 measurements were made:

(c) during a deep ramping cycle with a steep rate of rise, and

(d) during a ramping cycle with a rate of rise that is typical for the river.

A summary of the measured flow conditions is given below.

Table 3 Description of the ramping waves measured by ASR.

	Values at Hamilton recorder over the full ramping rise.		Data for the measurement period at the measurement site.						
Feature:	Peak flow	Ramping rise trough to peak	Rise in depth	Peak depth	Av. rise rate	Max. rise rate	Max. water slope S	Depth at max slope R	14RS
Site	[m^3/s]	[m]	[m]	[m]	[mm/min]	[mm/min]	[-]	[m]	[mm]
1 (a)	275	0.85	0.33	2.66	2	4.2	.000445	2.33	14.5
1 (b)	275	-	nil	2.78	nil	nil	.000370	2.78	14.4
2 (c)	300	1.01	0.92	2.87	1.9	3.3	.000310	2.06	8.9
2 (d)	250	0.69	0.58	2.37	1.8	2.7	.000408	1.86	10.6
Note: Peak flows are approximate as they are based on average water level-vs-flow ratings. The last column indicates the diameter of stable bed particles under uniform flow conditions.									

6.1. Discussion of ASR measurement results at Site 1:

In evaluating these measurements it should be noted that for uniform flows with equivalent energy gradients, the bed shear velocity, turbulence and bed material movement could be expected to be greater for the constant, steady flow (b) measurements than anywhere in the (a) ramping measurement range due to the greater flow depth at the measured location (2.78m –vs- 2.66m). The ramping rise (a) gives a steeper energy gradient than the steady flow (b) resulting in a similar reference stable stone size for both flow conditions (last column in Table 1). In reality, ASR's measurements (Fig. 6.1 in their report) show greater downstream velocity (u), increased turbulent energy (TKE) and a similar range in turbulent velocities (σ_u) for the ramped flow compared to the deeper steady flow. After the peak rate of rise of the ramping wave (a), both u and turbulent energy decreased to eventually reach the steady flow (b) values. Higher velocities and turbulence occurred during the rapid ramping rise than during the deeper steady flow.

ASR used a bed level sensor to record the elevation of a 2cm diameter area of the bed during the measurements. According to Fig 4.23 in the ASR (2004) report, the local bed elevation fell by ~ 15mm and then stabilised during the steady flow (b) measurements. During the (a) measurements, bed level fluctuated over a range of ~ 35mm on the rising limb of the ramping and then stabilised as peak depth was reached. The size of recorded steps in the bed surface gives a limit on the sizes of particles being moved by the flow. For (a), the movements indicate that some gravel transport was taking place during rising ramping conditions. For (b), initial scour of pebbles or sand particles ceased as the steady flow continued. Underwater video of the bed near the sensor showed intermittent movement of the largest pebbles. There was no evidence of bedform movement (sediment waves in the bed).

ASR also measured bed load transport with a Helley-Smith sampler. Rates were higher during the ramping than during the steady flow but both rates were low (~25g/min per metre bed width). Somewhat coarser sediment was collected during the ramping rise than during the higher steady flow (ASR Figs 4.27 and 4.28). Most samples indicated two dominant particles sizes of around 0.3mm and 12mm. The 12mm size is close to the reference size for particles that would not be moved in an equivalent uniform flow at this site. The maximum particle diameters in the collected bedload samples were around 40mm. The presence of these occasional large particles indicates that either the river turbulence was higher than under uniform channel reference conditions or larger particle movement was instigated by movement of neighbouring finer material.

6.2. Discussion of ASR measurements results at Site 2:

Fig. 6.2 in ASR's report shows that for both the ramping cases at Site 2, the maximum downstream velocity occurred well before the maximum water depth was reached. Downstream velocities, turbulent energy and σ_u were greater for the steeper wave (c) than for the normal wave (d). High turbulence levels continued past the peak in velocity for the steeper wave whereas turbulence appeared to decrease following the velocity peak of the normal ramping wave.

The bed level sensor indicated no change in bed level during the normal (d) ramping rise (ASR Fig. 4.24). Two 10mm deep holes were eroded and refilled under the sensor on the rising limb of the steep ramping cycle (c).

Bed material arrived intermittently in the bedload trap during both ramping cycles. For the steeper ramping (c), a single peak early on the rising limb was later followed by a rise to around 30 g/min per metre of bed width. The normal ramping also showed a single peak in bedload transport against a background rate of ~ 12g/min per metre of width. All bedload samples showed a dominant particle size of ~12mm. Sediment collected in the bedload trap showed a similar size range for both ramping waves (ASR Fig 4.29 and Fig. 4.30). The normal ramping (d) samples contained somewhat less fines than the steeper ramping cycle (c) samples (ASR Fig 4.26).

ASR estimated bed shear stress during their measurements. With a variety of assumptions about flow uniformity and velocity profile shape, they concluded there was not any significant enhancement of bed shear stress during ramping. As it is difficult to calculate shear stress under rapidly changing water level conditions, emphasis should be placed on their directly measured findings (described above) ahead of estimated shear stress values which required assumptions that may exclude the effects of ramping.

ASR also measured suspended sediment concentrations during the ramping measurements. For the dry weather conditions during the ramping investigations the level of suspended sediment will primarily be influenced by upstream bank erosion. The measured suspended sediment concentrations were higher for the deeper and steeper ramping waves (a) and (c) than for the other cases. Because of different travel times of flow surges and suspended sediment it is not possible to draw any other links between ramping and suspended sediment loading.

6.3. Conclusions from ramping measurements.

ASR's measurements demonstrate that ramping produces an increase in the hydraulic factors which are responsible for the entrainment and transport of bed material and the answer to the first crucial question is that there is evidence that ramping rises can increase sediment transport. The second crucial question relates to the significance of this increase and we discuss the measured rates of bedload transport.

Factors to consider are that the bedload sampler may not trap all of the finer sandy bed material and placing and raising it may dislodge a small amount of material into the trap. In addition, unless there is "carpet" bed material movement, bed load tends to move in "corridors" on a river bed. The position of the corridors can vary with time and there is no guarantee that the sites or measurements carried out by ASR were representative of the whole river bed. However, taken together, the measurements indicate that a "ballpark" figure of around 25g/min of bed material moves per metre width during the ramping rises at the two sites.

Assuming rounded estimates of 10 hours of ramping rise per day and a 100 m river width, 25g/min/m roughly indicates a daily bed material load of around 1.5 tons/day. A 100m long reach of river, degrading at the measured average rate of 30mm per year, is sufficient to produce this rate of bed load. In other words, the bed load rates measured during ramping are far too low to explain the observed rates of degradation.

This initial appraisal of the second crucial question would seem to indicate that the increase in transport due to ramping rise is very small in comparison to the transport rates that must occur in order to produce the observed degradation. Before this matter can be settled we must consider what conditions can produce degradation at the measured rate.

The trapped bedload samples displayed a non-homogenous range of particle sizes. The dominant particle diameter in the samples was similar to the indication of maximum moveable particle size (given in the last column of Table 1). For a bed with unlimited availability of all particle sizes it could be expected that the bedload would comprise smaller amounts of these larger particles (those near the limit of movement) and an increasing volume of finer particles (as their mobility increased with decreasing particle size).

The answer to the anomaly is that available finer particles have already been removed from the bed surface by previous flows of this size or smaller. The expected amounts of finer particles were not found in the bedload samples because they were not available on the river bed surface.

If the bed surface comprised 0.3mm sand, a moving carpet of sand would occur on the bed for the flow conditions of the measurements (the Shield's parameter was around unity, - sand waves are washed out and sheet flow develops for Shield's parameter > 0.8). Underwater video footage, taken near site 2 on a previous occasion, shows that extensive, low amplitude sheets of sandy, pebbly bedload can move over the Waikato bed during a flood.

If the bed surface contained ample supplies of 0.3mm sand as found below the bed surface (see Section 5 of this report), sediment transport formulae indicate that more than 300 tons/hour would be moving during the flows for the ramping measurements. This rate is more than sufficient to explain the average rate of degradation which is equivalent to around 20 tons per hour from a 34km reach, 100m wide.

It is concluded that during the conditions measured by ASR, if the sites are similar to the borehole locations, underlying fine particles were protected from erosion by a veneer of coarse particles. This type of feature is sometimes referred to as a *dynamic* armour layer. This term should not be confused with *static* armour layers which are persistent and enduring features.

The larger sizes that were moved by the ramping rises were able to be moved because they had not already been removed by previous flow conditions in the river. During the steeper ramping rise measurements more of the coarser protecting particles were being moved but no easily erodable alluvium was exposed on the bed. As there is degradation of the riverbed, either the gravel veneer must be transitory, allowing degradation to occur intermittently, or the two sites investigated are atypical of the river and are not degrading significantly. The ramping investigation sites lie close to cross-sections 154A (Site 1) and 146A (Site 2). Both sections show evidence of recent bed degradation. Two borehole locations (2 and 7) showed a 0.5m layer of gravel overlying the more easily erodable layers and similar conditions may exist at the ramping measurement sites. There is not sufficient evidence to determine whether the ramping measurement sites are temporarily covered with a gravel veneer or whether the measurements sites had deep gravel deposits on the bed surface.

Thus the answer to the second crucial question is not cut and dry. The flow conditions during ramping would produce significant erosion of the bed if it comprised the prevalent fine alluvium which is underlying the bed. Bore hole 3 shows this material can be present at the bed surface but low recovery rates from most other boreholes prevent identification of the surface layer. Until such information is available it is not possible to judge how much of the bed is protected by a veneer of larger particles and whether ramping can damage (or enhance) this protective veneer. If much of the bed is coated with a gravel layer, this must be moved by floods to allow degradation at the observed rate.

In this case the life-cycle of the gravel on the bed surface is as follows:

An old layer is destroyed (by gravel extraction, floods or any flows that have the ability to entrain the dominant fraction of the particle sizes forming the bed surface). Significant bed degradation occurs.

Flows return to normal levels but high levels of sand transport still occur, rapid bed degradation persists.

As normal flows continue, larger particles contained in the parent material or eroded from the local banks remain on the bed (these particles cannot come long distances from upstream because they cannot be of sufficient size to resist movement yet be readily transported).

Eventually the erosion resistant sizes become the dominant bed surface particle size, the veneer is re-established, bedload transport decreases to a minimal level and degradation stops.

At this stage an increase in flow could coarsen the armour layer, destroy patches of the armour layer or remove it completely.

Any significant armour layer in the degrading reaches of the Waikato must be fragile and ephemeral for two reasons:

- In the local parent material there are not ample supplies of particles of suitable size for armouring (see bed cores in Appendix II), and
- If the layer was stable or becoming progressively more armoured, the measured degradation rate would show signs of decreasing.

A further borehole at measurement site 2 is recommended to shed light on the situation (the precise location of site 2 is given in table 2).

Intensive monitoring of a typical degrading reach during floods and ramping cycles would be constructive to establish exactly when substantial bed degradation occurs.

7. Conclusions and Recommendations

There are several, previously undetected, high sills in the river bed. Because high sills help govern degradation by reducing water surface slope and velocities, the resilience of these sills is of importance. Hard strata in the bed could also constrain degradation. The seismic survey revealed 59 sites of potential hard strata between Horotiu and Narrows Bridge but no hard strata were evident in any boreholes. Recovery rates from the borehole cores were poor and no mapping of underlying strata was possible. The one borehole that intersected a seismically identified potential hard stratum showed the bed comprised gravel at this location. The boreholes showed strata up to 8m below the bed to be predominantly non-plastic sand, silt and fine gravel. Such materials are easily erodable. The existence of hard sills was not verified by the boreholes. Further boreholes are recommended to investigate the composition of four high sills because the general rate of bed degradation could rapidly accelerate should these sills be eroded.

There is evidence of local widening at a number of locations but overall the river is narrowing. The river morphology is highly dynamic and cyclic with previously widening reaches now narrowing and vice-versa. Degradation is greatest at narrow sections of the river.

Hydro ramping mobilises sediment sizes that would not be expected to move under steady flow conditions but, at the two sites investigated, very rapid ramping moved but did not break a protective surface layer of gravel on the bed.

The studies give no reliable evidence of any features that will prevent continued degradation or reduce its rate. The best estimates of future degradation are therefore based on extrapolation of present rates. This indicates that, unless constraints are encountered or there is widespread bank collapse, mean bed levels in Hamilton could fall to 1.5 metres below the present position over the next 50 years. Such unchecked degradation will eventually lead to bank collapse, undermining of riparian structures and headwards erosion of unprotected tributaries.

On the basis of this information, measures to manage future degradation should not be delayed. Most importantly, calculations of bank stability are essential to identify future hazards and to ascertain when bank collapse will begin to supply sufficient sediment to reduce the present degradation rate. A continuation of the bathymetric surveys and LiDAR monitoring of banks every 5 – 10 years is recommended in order to detect future irregularities. Intensive monitoring of a typical degrading reach would be constructive to establish precisely when episodic bed degradation occurs.

8. Results of Follow-up Investigations

In July 2005, additional boreholes were drilled at the locations recommended in Table 2 and carbon dating of organic material was carried out. In addition, a discussion was requested on the factors contributing to the present degradation. These results are presented below.

8.1. Additional boreholes and carbon dating

Additional boreholes were drilled at riverbed high points (Sills A-D on Figure 10) and at measurement sites 1 and 2. Logs from these bores are attached as Appendix 3.

Cores from Sills B, C and D and Sites 1 and 2 (all within Hamilton city) revealed loose, recent alluvium over the full borehole depth (depths ranged from ~ 5m to ~ 8m below river bed level).

Sill A, located approx. 1.5 km upstream of Horotiu Bridge (Fig. 2), comprised 1m of recent sand overlying a 2.5 m layer of peaty material overlying probable Hinuera formation.

Carbon dating of organic matter found in boreholes at Sill A, Sill D and Site 1 was carried out. The results are given in Appendix 4 and are summarised in Table 4.

Table 4. Age of organic fragments according to carbon dating.

Location	Sample depth in metres below bed surface.	Surrounding material	Sample age in years before present.
Sill A	1 - 3.5	Silty peat with wood fragments.	> 45,000 BP
Sill D	4.5 - 5.5	Gravelly fine to coarse sand, rounded pumice up to 10mm.	2040 +/- 38 BP
Site 1	6.5 - 7.5	Sandy fine to medium gravel, pumice up to 20mm.	2051 +/- 62 BP

The Sill D and Site 1 samples show the organic material was exterminated at the time of Taupo eruptions around 35 BC. These deep alluvial deposits also contain pumice and it can be assumed they result either from deposition of Taupo eruption material or from later re-deposition of eroded Taupo eruption material.

The carbon dates and bore logs confirm that the high sills through Hamilton city are geologically recent, easily eroded alluvium that is unlikely to constrain the present degradation.

Carbon dating of the Sill A sample, taken near the bed surface 1.5 km upstream of Horotiu Bridge, indicated material over 45,000 years old. The presence of such old material overlying probable Hinuera formation indicates that this sill does not comprise recent aggradational deposits. The upper 3.5 m of sand and silty peat found at this location is unlikely to offer a barrier that is resistant to degradation.

8.2. Relative importance of factors causing degradation

Mechanisms that have been suggested which could contribute to the degradation processes presently underway in the middle reaches of the Waikato River include:

- Continuing historic geomorphologic processes
- Sand mining
- Additional flows due to Tongariro Power Development diversions
- Ramping of flows to meet peak electricity demands
- Upstream hydro dams
- River management practices
- Land use changes

These factors are discussed in turn.

- Continuing historic geomorphologic processes

If the middle Waikato River has been degrading historically, this trend could explain or augment the present degradation.

Cross-section surveys indicate degradation became apparent in Hamilton in the 1960's and upstream of Hamilton in the 1950's. Trends prior to filling of the Karapiro dam in 1947 are of interest to put the present degradation in context.

Schofield (1967) stated that "Since 130 AD the bed of the Waikato River has risen 20 to 30 ft at Huntly, Taupiri, Ngaruawahia and Karapiro" He based this on a study of tributaries. For example, in the 1960s the average depth of the Waikato was 10 to 15 ft where it joins the Waipa River. The Waipa however, deepened from 20 – 22 ft at 300 m above its Waikato confluence to 30 – 35 ft at 800 m above the confluence. Schofield thus concluded there had been aggradation within the Waikato 20 ft (6.2 m) greater than in the Waipa River. He claimed "dams have only been constructed within the last half century and can have had little effect on 30 ft of aggradation". He attributes likely causes for aggradation since 130 AD to be "a combination of man-made erosion and rise in sea level".

Kear et al (1964) in notes to the Hamilton Geological map N65, state: "From evidence supplied by the inter-relationships of the Taupo Pumice Alluvium and more recent sediments, aggradation within the Waikato River is estimated to have been 25 to 30 ft since 150 AD., i.e. an average rate of about 1 ft every 60 years" (approx +5mm/yr). "Surveys of the Waikato River show that within this century the rate of aggradation may have been twice as great. Of a number of causes, man-made erosion since the arrival of the Maoris is probably the most likely."

Dr Hicks' 2003 evidence gives water level records between 1921 and 1961 from the old water treatment plant. They indicate a mild aggradation trend prior to 1958.

These three independent results confirm that the middle reaches of the Waikato were not degrading prior to the present spate of degradation.

Historical processes may have indirectly contributed to the present degradation by placing the material that is now being eroded. In terms of a mechanism causing the present degradation, the continuation of a historic geomorphic trend can essentially be ruled out.

- Sand mining

Sufficient sand mining took place up to the mid 1970s to influence bed levels at the time. Since sand mining has ceased degradation rates have not decreased.

It could be that sand mining removed a protective gravel armour layer (if one was present) and thus instigated degradation at certain locations. However, prior to the present degradation episode, the river was mildly aggrading and aggrading rivers are not conducive to formation of a gravel armour layer. Samples taken in 1964 showed the Waikato bed to be dominated by sand sizes between the Narrows and the Waipa river junction. It is therefore unlikely that sand mining contributed to the present degradation by removal of a protective surface layer.

The unknown rate of excess sediment inflow causing the mild aggradation prior to the 1960's may have equaled or exceeded the volumes of sand mined. Thus, it is concluded that while sand mining may have aggravated past degradation, its contribution to the present degradation rate is very low.

- Additional flows due to Tongariro Power Development diversions

Waikato River flows are increased as a result of Tongariro Power Scheme diversions from the Whanganui R. headwaters and L. Moawhango into L. Taupo. On average, the Waikato discharge has been increased by 31 m^3/s so that the Tongariro scheme contributes 12% of the 261 m^3/s mean flow through Hamilton. Earlier estimates have suggested this will increase the bed material transport capacity by 17% at Hamilton Traffic Bridge (Hicks, 2003). The problem with this type of calculation is that in the middle reaches of the Waikato River and at constricted sites such as the Traffic Bridge in particular, the sediment transport rate is supply limited and actual transport bears little relation to transport capacity. The relevant factor is the entrainment rate. The Stage II investigations indicate that, at the sites measured, the entrainment process is episodic, only taking place during and following flood surges.

Relevant factors to be considered are:

1. Tongariro flow diversions are not permitted when L. Taupo levels are high, and

2. Is the additional water from the Tongariro catchments used to augment base flows or to fuel peak generation demand?

In light of the above, it is considered that the increase in Waikato flow due to Tongariro diversions is unlikely to occur during periods with high sediment mobility and consequently the Tongariro Scheme water will not have major influence on the degradation rates in middle Waikato River reaches.

- Ramping flows to meet peak electricity demands

The Stage II investigations (ASR 2004) showed that hydro ramping mobilises sediment sizes that would not be expected to move under steady flow conditions but transport rates were low. At the two sites investigated, very rapid ramping moved but did not break a protective surface layer of gravel on the bed. Without the protective gravel found at the measurement sites, ramping waves could move enormous volumes of sand; - sufficient to explain the present average degradation rate (Section 6.3). Ramping therefore has the potential to significantly affect degradation rates, depending on the composition of the river bed surface.

- Upstream hydro dams

The hydro dams upstream of Cambridge currently trap bed material that would have been transported past Karapiro prior to construction of the dams. The trapped volume is estimated to be over 100,000 m^3/yr which is similar to the average annual volume of degradation between Karapiro and Ngaruawahia. This indicates that the river is degrading downstream of Karapiro in order to recover the deficit of bed material created by the upstream hydro lakes (Hicks, 2003).

Extrapolation of mean bed level planes fitted at the times of cross-section surveys taken in middle Waikato reaches, shows these planes intersect in the vicinity of Karapiro Dam (Smart 2003).

Cross-sections at Pukete boat ramp, downstream of the Narrows Bridge and the specific gauge record at Hamilton show the time series of falling mean bed levels is best fitted by a linear trend when the start of degradation is taken to occur in 1947 (Smart 2003). The lake behind Karapiro Dam was filled in 1947.

These facts confirm that the present degradation is primarily due to upstream hydro dams.

- River management practices

Bank protection works such as riprap and riparian planting can reduce potential sediment inputs by preventing bank erosion. Had such bank erosion not been prevented, it can be argued that the bed erosion would have been lower due to increased sediment supply from the banks and a consequent increase in flow cross-sectional area. This argument requires the presence of upstream dams *apriori*, in order to create a situation of sediment deficit. Thus any effect of such bank protection practices is a secondary effect and not a primary cause of the present degradation.

- Land use changes

Changes in land use have the potential to alter both water and sediment yields from catchments. The question is therefore focused on any land use changes that could affect the river bedload budget.

Any future proposals to fell large blocks of forest in the Waikato catchments should be considered carefully as clear felling of large areas could significantly increase peak flood flows.

Climate change protocols mean that the long-term scenario for future land use is likely to be in the other direction, - towards more forests. Generally, an increase in vegetation reduces water runoff from all but extreme rainfall events and reduces sediment runoff under all conditions. This scenario would reduce streamflow into the Waikato.

In terms of the present situation it is not likely that land use changes have had any substantial effect on degradation as a result of significant changes in river flow.

With regard to sediment yield, any changes upstream of Karapiro are not relevant because such sediment is trapped in the hydro dams. The catchment area of tributaries between Karapiro and Ngaruawahia is only 480 square kilometres and no major land use changes are known to have occurred in this area.

It is concluded that recent land use changes are not having any significant effect on the bedload sediment balance in the middle Waikato River.

Ranking of effects.

The above mechanisms are ranked in Table 5 with indicative ranges of influence on degradation.

Table 5. Relative importance of factors causing the present degradation.

Process	Lower estimate	Upper estimate
Upstream hydro dams	85%	100%
Ramping of flows	2%	20%
Sand mining	0%	10%
Tongariro diversions	2%	8%
Land use changes	0%	8%
River management	0%	5%
Geomorphologic processes	-10%	0%

Note: As all lower (or upper) estimates in Table 1 will not coincide, the columns do not add to 100%.

9. Appendix 1 References

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