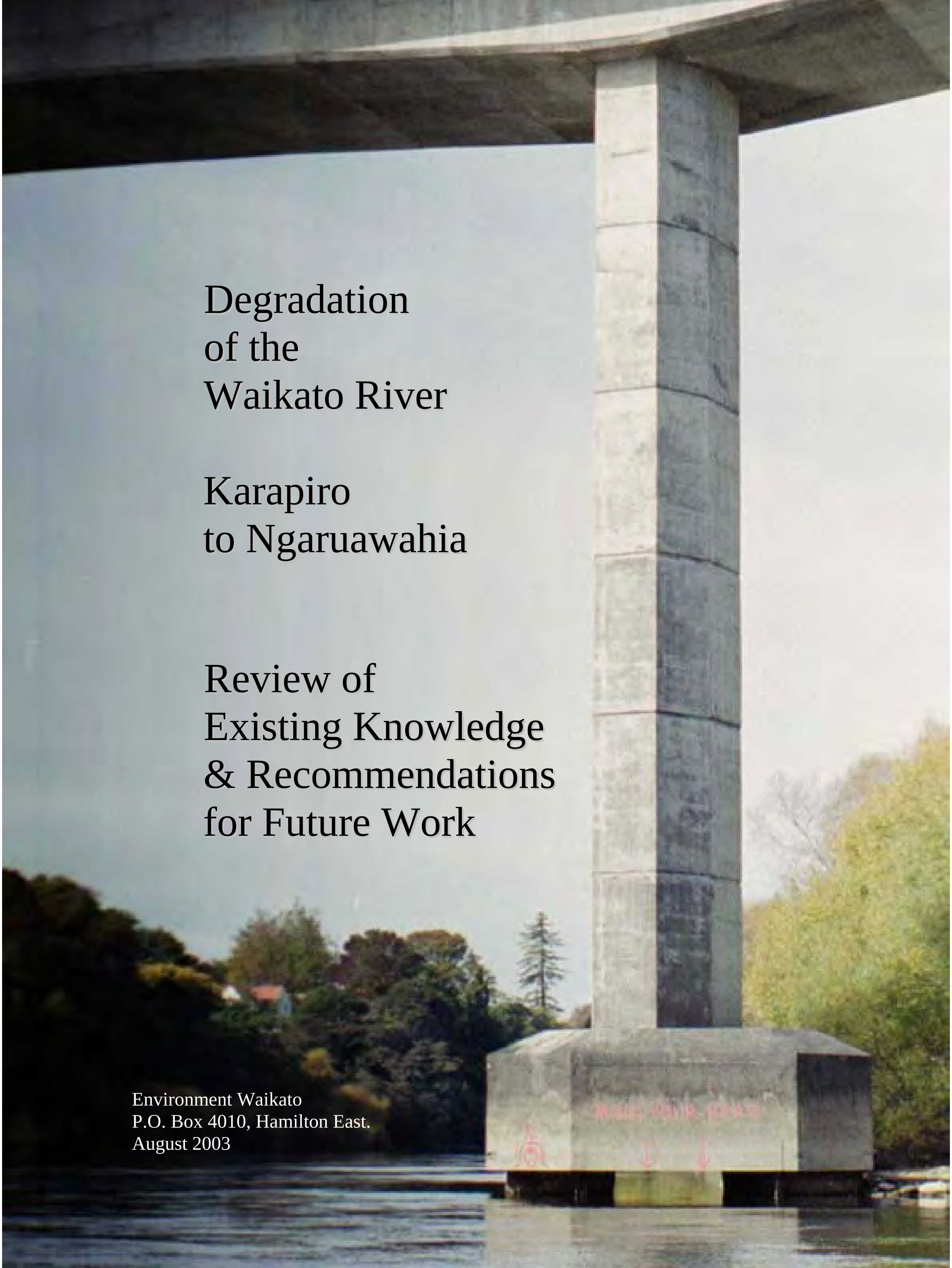

# Degradation of the Waikato River

## Karapiro to Ngaruawahia

## Review of Existing Knowledge & Recommendations for Future Work

Environment Waikato
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August 2003

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## Review of Existing Knowledge & Recommendations for Future Work

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# 1 Summary

An inspection of the Karapiro – Ngaruawahia reaches of the Waikato River reveals signs of active degradation, especially between Horotiu and Cambridge. The signs include exposure of bridge piles and failure of banks. The primary cause of the degradation is Karapiro Dam, which cuts sediment supply from upstream. Degradation started in Hamilton in the 1960's and has been aggravated by past sand extraction.

Measurements of degradation trends are obscured by areal and temporal variations in the river bed. Removing local variations shows mean bed levels through Hamilton follow a sloping plane. The slope of the plane is getting steeper with time. Long-term, the bed plane level is falling steadily at approx 32 mm/year just downstream of Hamilton and at 17 mm/year just upstream of Hamilton. There is no evidence of any decrease in this rate. Extrapolating the plane in the upstream direction shows that its origin (or hinge) lies in the vicinity of Karapiro Dam.

Within Hamilton, water levels are not falling as fast as the mean bed level and the rate of water level fall is decreasing. The Victoria Bridge water levels are falling by around 20 mm/year at present (2003) and extrapolating historical trends shows water levels could be falling at around 11 mm/year in 2050. The difference between the steady fall in mean bed level and a decreasing rate of fall in water level can be explained if erosion resistant bed sills are controlling water levels or if the river is widening.

Two potentially serious situations could develop:

- Degradation can produce a situation of critical bank stability that causes a river to switch from deepening to widening,
- Weaker layers may exist below the river bed and cause a sudden increase in degradation where these layers are exposed.

Measurements and analyses to further investigate these situations are recommended.

In addition, because erosion can be increased by flow surges, measurements during ramping are necessary to establish whether the present hydro peak load generation rules will accelerate degradation.

# 2 Background

Historical bed degradation between Karapiro Dam and Ngaruawahia, and the unknown potential for future degradation in the Waikato River is an issue of concern to Environment Waikato. The causes of this degradation and remedies for the future are sought.

This report involves the first stage of technical investigations to estimate expected future changes in bed level. It focuses on reviewing existing reports and information and forms a basis for further technical investigations and subsequent development of a management plan to deal with the impacts of bed level changes. Statements in the report that are not referenced, are the views of the author.

# 3 Degradation Causes, Processes and Remedies

Degradation is a response to a disruption of the balance between the rate at which sediment is supplied to a river and the sediment transporting capacity of the river. The main factors that determine sediment transport capacity are expressed by Lane's 1955 relation:

$$q_s \propto Q\, S / d_{50}$$

where $q_s$ is the unit bed-material discharge, $Q$ is the channel forming discharge, $S$ is the channel gradient and $d_{50}$ is the median grain size of the bed material.

While this relation has been improved upon by more recent sediment transport formulae that are based on bed shear stress, it contains the fundamentals for a basic understanding of sediment transport; - transport capacity increases if the flow or slope increases or if the size of available sediment decreases, transport capacity decreases if the flow or slope decreases or if the size of available sediment increases.

What Lane's relation does not account for is that there is a threshold flow below which particular sediment sizes cannot be entrained. Depending on the level of this threshold, changes in flow regime may periodically raise flows above the threshold at times when the mean flow would lie below the threshold.

In the Waikato River below Karapiro, the long-term flow has increased and the channel slope has remained relatively constant or steepened. Thus Lane's relation predicts an increase in bed material transport capacity. More importantly, dams have cut off the supply of bed material from upstream and introduced more fluctuation into the flow regime.

The effect of dams has long been established. Leopold *et al* (1964) state, "In addition to creating changes in flow, dams with large storage capacity trap virtually 95 to 99% of the sediment that previously passed through the reach in which the dam is located. Thus clear water is released below the dam in place of the sediment-laden flows that existed prior to construction. The combination of clear water and changing flow regimen leads to erosion of the channel and lowering or degradation of the bed of the channel below the dam."

Degradation is causing serious problems around the world, particularly in Europe. Italian rivers have been subject to human modifications since Roman times. Rinaldi and Surian (2002) report that while the early modifications were chanelisations and diversions, since the $20^{th}$ century the main disturbances have been construction of dams and sediment mining. They report that incision and narrowing have resulted, particularly over the last decades. Single thread rivers have tended to incise whereas braided rivers tend to narrow. The incision is typically 3-4 m but in some cases more than 10 m. Trends measured on the Po, Arno and Piave Rivers show that incision is more intense immediately after a disturbance and then slows asymptotically. The larger the river, the longer the restabilisation time.

In Austria, almost all large rivers show bed degradation tendencies. The Danube downstream of Vienna is degrading at around 30 mm/yr, the Drau River, around 10-20 mm/yr and the Salzach River, up to 70 mm/yr (degrading 7m over 100 years). In the Danube, degradation eroded the quaternary gravel bed and exposed underlying finer tertiary material in some places. To halt a potential dramatic rise in degradation rate, the Local Authorities have lined these areas with rock riprap. In the Drau River, Habersack (1997) shows a mild correlation between substrate grain size and rate of degradation, meaning that the smaller the underlying riverbed material, the larger the degradation rate. Substrate with a median particle size of 40 mm had no degradation, whereas Drau river reaches with a median particle size of around 30 mm degraded at up to 20 mm/yr.

The Flokas Dam on the Alfios River in Greece, was completed in 1968. Gravel mining took place downstream of the dam extracting around 17.4 million cubic metres from 1967 – 1996. Rapid degradation and channel widening occurred. The average rate of degradation is estimated to be around 200-270 mm/yr and the banks have eroded at a rate of 3-4 m/yr over the last decade (Nicholas *et al*, 1999).

## 3.1 U.S. Waterways Experiment Station (WES) Recommendations.

The WES ‘Stream investigation and streambank stabilization handbook’ (Biedenharn *et al*, 1997) gives the following information.

Construction of a dam has a direct impact on the downstream flow and sediment regime. Channel adjustments to the altered flow duration and sediment loads include changes in the bed material, bed elevation, channel width, plan form, and vegetation. Generally, the initial response downstream of a dam is degradation of the channel bed close to the dam and sedimentation further downstream due to increased supply from the degrading reach. This is the typical response most commonly anticipated downstream of a dam. Degradation may migrate downstream with time, but generally it is most significant during the first years following closure of the dam.

As degradation proceeds through a system, the channel bank heights and angles are increased, which reduces the bank stability with respect to mass failures under gravity. If degradation continues, eventually the banks become unstable and fail. Bank failures may then no longer be localized at channel bends, but rather may also be occurring along both banks in straight reaches on a system-wide basis. When this occurs, conventional bank stabilization measures are generally not suitable, and a more comprehensive treatment plan involving grade control or flow control dams, diversion structures, etc., is required.

Assessing the need for remedial measures requires not only a quantification of the active processes of degradation, but also knowledge of the erodibility of bed and substrate materials throughout the entire system, because the rate and magnitude of degradation is very sensitive to bed erodibility. Even with ample data, the erodibility of cohesive soils and weak rocks cannot be accurately predicted. Numerical models do not account for cohesive materials well, and often the best approach is an empirical one, based on the known historical behavior of the particular system in question.

With regard to quantifying degradation, the WES handbook suggests that there are certain limitations that should be considered when comparing surveys on a river system. In comparing profiles it is often difficult to determine any distinct trends of degradation if there are large scour holes, particularly at channel bends. The existence of very deep, local scour holes may completely obscure temporal variations in the thalweg.

The handbook recommends that one of the most useful tools for assessing the historical stability of a river is the specific gauge record. A specific gauge record applies to a particular gauging location. It is a graph of the river stage for a specified discharge plotted against time.

## 3.2 Degradation Rate

The volumetric entrainment rate, adjusted for porespace, per unit area of bed, gives the degradation rate (bank erosion being neglected). Where a riverbed comprises loose erodable alluvium, the entrainment rate is the difference between the rate of sediment input from upstream and the local transport capacity. Where a riverbed is formed from cohesive or indurated material and transport capacity exceeds sediment input, the entrainment rate is limited by the rate at which particles can be detached or abraded from the bed. Loss of cohesive or indurated material is practically irreversible (over timescales of interest in this study) because any re-deposition comprises looser alluvium.

Darby and Simon (1999) state “Degradation is initially rapid and then slows asymptotically as the process ameliorates the imbalance between sediment-transporting capacity and sediment supply over time. As the bed degrades, heightened sediment loads, channel gradients and a host of other controlling variables decrease non-linearly with time. Bank heights also increase, although it is not until the critical height and angle of the bank is reached that they begin to fail and the channel begins to widen. The critical height is largely a function of the shear strength of the bank materials and fluvial erosion at the bank toe.”

The rate of degradation will be reduced or eventually stopped by several mechanisms:

- Degradation can flatten the river slope downstream of a dam and the slope may become so flat that the flow is not competent to transport the available materials,
- Reservoir storage can be used to reduce downstream flood peaks and hence the peak sediment transporting capacity of the river,
- An armour layer may form if suitable sediment particles are available on the river bed,
- Degradation may lead to bank erosion and down cutting of tributaries which, in turn, can supply additional sediment input or armouring material,
- Degrading incised channels commonly respond by a “sudden switching of the locus of channel instability from deepening to widening” (Darby and Simon, 1999).

## 3.3 Armour layers

In situations where there is no replenishment of bed material from upstream, armour layer formation requires the presence of a quantity of bed particles large enough to resist erosion. Winnowing of finer particles then leaves the bed coated with these erosion resistant particles. If there are not sufficient large particles or if the large particles promptly break down to smaller sizes, an armour layer will not form. Armour layers are destroyed when there are flood flows large enough to move the particles that form the layer and degradation recommences.

## 3.4 Importance of Bed Load

Bed load is sediment that rolls or skips along the riverbed. Where bed load material supply exceeds the local bed load transport capacity of the flow, bed load is deposited and the riverbed aggrades (rises). Where bed load input is roughly in equilibrium with the local transport capacity a carpet of bed load material can help protect the channel from erosion. Where there is a deficit of bed load input, erosion occurs because local bed material is directly exposed to river shear stresses and to the intermittent erosive impacts of bed load particles.

## 3.5 Ramping

Reservoir storage can be used to create flood waves as well as dampen them. The process of releasing storage to generate at times of peak electricity demand creates diurnal flood waves. This hydro operating technique is known as ramping.

For some time it has been known that the level of bed shear stress causing incipient motion of sediment particles (the critical shear stress) depends on the intensity of turbulent fluctuations in the flow. For wind erosion, Chepil and Woodruff (1963) found the critical entrainment shear stress varies inversely with $(1+3\sigma_p/p)$ where p is the average pressure acting on the bed and $\sigma_p$ is the standard deviation of pressure fluctuations. In other words, the greater the flow turbulence, the lower the average bed shear stress required to entrain sediment grains. For experimental data $\sigma_p$ ranges from p/3 to 2p/3 indicating that there can be a variation of approximately ±30% in critical shear stress depending on the intensity of flow turbulence. This means conditions exist whereby turbulent low flows can cause more serious erosion than higher, less turbulent flows.

Hayashi et al (1988) studied flood waves and found that turbulence intensity was greater on a rising flood than at the same water depth of a falling flood. This effect was also noted in the lower Clutha River when Smart (1990) measured turbulent velocities in the river resulting from ramping of Roxburgh hydro station some 100 km upstream. The maximum rate of rise in the Clutha was 240 mm/hr and much higher velocity fluctuations occurred during rising flows than were measured prior to the arrival of a generation wave. The fluctuations were much more intense on rising stages than at the same water depth on the falling stages of a generation cycle. The effect has been confirmed by laboratory studies of Song & Graf (1996) and Hunt (1997) who found that:

- for the entire range of flow depths on the rising and falling stages of flood waves the turbulence intensity is greater for steeper flood waves than for slowly rising and falling flood waves,
- the turbulence intensity is greater on the rising stage of hydrographs than for the same depth on the falling stage, except towards the tail of the flood,
- the return of the turbulent intensity to the pre-flood base flow magnitude was not complete until after the flood has passed, and
- the peak in turbulence intensity occurred first, before the maximum bed shear stress, followed by the peak flow rate, peak velocity, and these all occurred before the peak depth.

While these reports give strong evidence that rising flood waves caused by ramping will increase the level of turbulence in a river, it remains to be quantified as to whether the increase in turbulence from ramping is significant in terms of sediment movement in the Waikato River. Any adverse effects of ramping are likely to be amplified if the ramping is superposed on a rising flood.

## 3.6 Land Use Change

Changes in vegetation cover have the potential to alter both water and sediment yields from catchments. Generally, an increase in vegetation reduces water runoff from all but extreme rainfall events and reduces sediment runoff under all conditions. For conversion of scrub or pasture to pines, Duncan (1996) reports that where less than about 20% of the cover is altered, any changes in flows are obscured by variations in flow caused by climatic factors. Considering that it is unlikely that an additional 20% of the Waikato catchment will be converted to forestry over the next decades, it is not expected that landuse change will have any significant effect on degradation through 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 it is unlikely that vegetation changes in this area will have any significant effect on the sediment balance in the river. There is one place that vegetation can have a marked effect and that is on the river banks. Bank vegetation changes can affect flow resistance and bank stability as discussed below.

## 3.7 Possible Remedial Measures

If degradation reaches the point where the stability of banks or bridges is in danger the overseas practice has been to construct sills across the riverbed below the endangered structures. Usually a series of sills is required, each to protect the toe of the next upstream sill. In New Zealand, riprap sills have been placed on the Wairoa R. in Nelson to reduce degradation. Weir construction could fulfil a similar purpose.

Removing bank vegetation at appropriate locations can encourage erosion at these sites. A resulting increase in bed load will then help reduce degradation of the bed. This technique has been successfully used in Europe. The Thur River in Switzerland suffered from degradation in upper reaches and deposition in lower reaches following realignment, narrowing and bank protection works undertaken over the past century. The degradation was advancing downstream at a rate of around 200 m/yr. In order to correct the bedload imbalance of the river, bank protection was removed allowing bank erosion to take place at selected sites. With certain precautions such as securing large trees to prevent them floating downstream to jam on bridge piles, the works have been judged to be highly successful (Jaeggi & Oplatka, 2001).

# 4 Waikato River Inspection, 7 May 2003 (low flow conditions).

**Summary of observations**.

The river displays many signs of significant and active degradation. These include bank failure, trees leaning towards the river and exposed bridge piles. The number of leaning trees and failing bank sites increases moving from the Waipa confluence in an upstream direction towards Karapiro. Vegetation protects the banks from raw erosion scars. The main form of erosion appears to be degradation of the channel bed causing intermittent slipping of the banks.

Detailed observations follow, ordered from downstream to upstream.

## 4.1 Waipa confluence – Horotiu Rd Bridge.

The banks are low and willow protected with some sandy beaches. Minor bank failures are evident in places.

Only minor tributaries enter.

Alder and poplar trees protect low banks downstream of Horotiu Bridge.

## 4.2 Horotiu Rd Bridge – Pukete Bridge.

Slight bank erosion is evident just upstream of Horutiu Rd Bridge.

Riparian trees lean towards the river indicating bank failure has occurred.

Leaning trees are straight (not curved towards vertical) suggesting that the bank movement is recent (0 – 8 years).

Indurated strata protect the banks 0.5 km upstream of Horotiu Rd Bridge.

Further upstream willows protect the banks and there are sporadic sand beaches.

Occasional trees lean in towards the river.

Downstream of the Sewer Bridge hard strata protect the banks.

Minor bank erosion occurs in places on the outside of curves from 0.5 – 2km downstream of Pukete Bridge.

## 4.3 Pukete Bridge – Fairfield Br.

Pukete Bridge is only some 5 years old but the piles are now exposed below the pile caps of the bridge piers as shown in Fig. 1.

River banks have willow protection and sandy beaches.

Hard strata protect the left bank at the downstream end of the golf course.

A mild erosion scar is visible on the right bank at the upstream end of the golf course.

Mild erosion scars occur on the right bank 1 km downstream of Fairfield Bridge.

Retaining walls have been built to hold the left bank 0.4 km downstream of Fairfield Bridge.

**Figure 1  Pukete Bridge showing piles exposed below the pier cap.**

### 4.4 Fairfield Bridge – Boundary Road Bridge.

Fig. 2 shows the Waitawhiriwhiri Stream confluence is hanging on the left bank of the Waikato. It has a weir and dumped rock for protection against down cutting.

**Figure 2  Waitawhiriwhiri Stream confluence.**

Fig. 3 shows the Boundary Road Bridge pier.

**Figure 3  Boundary Road Bridge looking upstream**

## 4.5 Boundary Road Bridge – Claudelands Bridge.

At the Boundary Road Bridge pier caps are undercut exposing the piles and reinforcing bars.

Minor bank erosion scars occur on the left bank just downstream of Claudelands Bridge.

Exposed piles below Claudelands Road bridge piers are shown in Fig. 4.

**Figure 4  Claudelands Road and Rail Bridges**

**Figure 5  Piers of Claudelands Bridges, looking upstream to Victoria St Bridge**

### 4.6 Claudelands Bridge – Victoria Street Bridge.

The left bank above the bridge shows strata that appear to be highly resistant to erosion.

Mid-reach it looks as if sand has recently been excavated from the centre of the river to form a beach on the right bank of the river.

### 4.7 Victoria Street Bridge – Cobham Bridge.

On the left bank just upstream of Victoria Street Bridge is an old wharf deck, now high and dry approximately 3m above a beach.

Rubble has been dumped to protect the right bank 0.5 km upstream of Victoria Street Bridge and riprap has been dumped to protect the bank 1 km upstream of Victoria Street Bridge.

Hospital Drain entrance is hanging as shown in Fig. 6.

Riparian trees are leaning towards the river.

**Figure 6  Hospital Drain Confluence**

Just downstream of Graham's Island, more trees on the left bank are leaning in towards the river.

Hard strata are evident in the banks just upstream of Graham's Island.

Cobham Bridge piles are exposed beneath the pier as shown in Fig. 7.

**Figure 7  Cobham Bridge Pier**

### 4.8 Cobham Bridge – Narrows Bridge.

Mangakotukutuku Stream enters on the left bank 0.5 km upstream of Cobham Bridge. Down-cutting is causing willows to fall into the river as shown in Fig. 8.

0.8 km upstream of Cobham Bridge trees are falling from the left bank into the river.

The high right bank 1.8 km upstream of Cobham Bridge has minor erosion scars visible.

There is slope failure of the left bank, 2 km upstream of Cobham Bridge.

The Mangaonua Tributary enters 3 km upstream of Cobham Bridge and is down-cutting to the river level.

1 km upstream of this tributary trees on the left bank are falling into the river.

1.5 km upstream of the tributary the right bank has moderate erosion scars.

The left bank is eroding 2.5 km upstream of the tributary (near Stubbs Road).

The left bank is eroding 0.5 km upstream of Stubbs Road and trees are falling into the river from the right bank.

1 km downstream of the Narrows Bridge the bank is collapsing into the river as shown in Fig. 9.

**Figure 8 Mangakotukutuku Stream Confluence**

**Figure 9  Bank collapse downstream of the Narrows Bridge**

### 4.9 Narrows Bridge – McEldownie Road.

Hard banks confine the river for approx 1 km upstream of the Narrows Bridge. Slope failure of the left bank is occurring at the top end of the 1km reach.

Mystery Creek joins the Waikato 2 km upstream of the Narrows Bridge, the creek has steep banks (Fig. 10). Two Totara trees help protect the confluence against erosion.

The Waikato right bank upstream of Mystery Creek confluence is eroding. The left bank alongside the Lochiel golf course is slipping in places.

In the vicinity of the Mystery Creek Museum, riparian trees are leaning towards the river. A further 1.5 km upstream of this point there are leaning trees, falling trees, bank slumps and bank erosion scars. Near McEldownie Road both banks are slipping towards the river.

**Figure 10  Mystery Creek**

### 4.10 McEldownie Road – Cambridge

The Mangawhero Tributary entrance is hidden by willow trees 1 km upstream of McEldownie Road.

2 km upstream of McEldownie Road slope failure and erosion is evident on the left bank. A further 0.5 km upstream the river narrows between hard banks then widens with a small island outcrop in the channel.

Alongside the oxidation ponds there is a narrow gorge and at the entrance to this gorge the bank is slipping into the channel. Trees leaning into the river (see Fig. 11) show there has been episodic and recent bank failure caused by erosion of the foot of the bank. The bank collapse is evident on both sides of the river indicating that extensive bed degradation has recently occurred in this reach. The position of the angle correction on trees on the left side of Fig. 11 indicates this bank slipped 10 – 15 years ago. The straight leaning trees indicate recent bank movement.

**Figure 11 Upstream view near the oxidation ponds showing evidence of recent tree rotation (centre and right arrows) and old rotation (left arrows).**

For the remaining 3 km to the center of Cambridge the river is narrow and deeply entrenched between high banks with inwards leaning trees, fallen trees and slipping side slopes evident.

### 4.11 Cambridge – Karapiro

The Karapiro Stream joins the Waikato at Cambridge. Coarse sand bars at the confluence indicate that this tributary is supplying quantities of sediment to the Waikato during floods.

Above this confluence the Waikato becomes very narrow. The reach from 0.6 km to 2 km upstream of the Karapiro Stm confluence is a relatively recent channel that has cut off the previous river channel that flowed behind the golf course. The upstream part of this cutoff is very narrow with vertical walls (Fig. 12). The channel then widens slightly and 2.5 km upstream of Karapiro Stm confluence a small down-cutting tributary enters on the left bank. Upstream of this tributary there are high cliffs on either side of the river and sites of slumping, slips and bank erosion.

**Figure 12 View from narrow reach looking downstream towards Cambridge showing bank slippage and falling trees.**

In the final 1 km to the Karapiro Dam the river bed is steeper and shallower with rapids over bedrock in places.

## 5 Particular Studies of the Waikato River

For each of the following studies, only information relevant to degradation of the Karapiro – Ngarauwahia reaches of the Waikato River is described. Comments and recommendations do not necessarily reflect the opinions or interpretations of the original report authors.

### 5.1 Waikato River Bank Stability at Hamilton City, OPUS Report 2166, 2001.

Calculations of the safety of the left bank at Claudelands Bridge were made using a mathematical model.

The Claudelands site was chosen for specific analysis because it had the steepest and highest banks, known geology, and cross section records available.

Three Claudelands Bridge situations were modelled, - the 1987 bed cross section, the 1987 bed lowered by 1 metre and the 1998 bed cross section. For the worst case scenario the study found that the sensitivity of gross river bank stability to bed level changes was “small but significant”. Assuming that a safety factor of 1.2 was applicable to the 1998 situation, the model indicated that with bed levels 1 m below the 1987 level, the safety factor reduced to 1.01

The report discussed the stability of other Hamilton bridges in the light of the Claudelands analysis. It concludes that “if the existing situation is marginal, any bed degradation, especially below the 1987 level, may be sufficient to trigger bank failure”.

Comments

Strong banks tend to be steeper than easily erodable banks. Thus by selecting the Claudelands site, with steepest banks, the report authors may have chosen one of the more stable sites.

In the previous section on the field inspection, it was noted that the bank at the Claudelands site appeared resistant to erosion whereas banks at many other locations had recently failed. Furthermore, at the time of the 1998 cross section, the bed at the base of the Claudelands site was more than 1 metre higher than its 1987 level (i.e. the bank toe was aggrading). The 2002 survey of Basheer *et al* shows that further deposition has occurred at the toe of the modelled site (i.e. the bed is still aggrading at the foot of the Claudelands site). Thus the modelled site is not typical of the many degrading locations on the river. However, the aggraded deposits at Claudelands Bridge could rapidly re-scour if a shift in the thalweg directed the river towards the left bank.

Recommendations

- Calculations of bank stability should be made at locations where significant near-bank degradation is occurring as well as beside banks supporting important infrastructure.
- Regular monitoring of bed cross-sections should be carried out at critical locations such as bridge sites.

## 5.2 1994 Barnett Consultants Morphological Modelling Study.

Barnett Consultants Ltd undertook a numerical model study of the Waikato, from Karapiro downstream. The modelling assumed that bed material in each reach was of uniform size and was being transported under "equilibrium" conditions whereby there was always sediment available to match the transport capacity. Models calibrated with information collected up to 1988 were used to predict bed levels until 2044.

A grain size investigation showed that a wide range of sizes is present on the riverbed. Median grain sizes greater than 10mm were not found downstream of the Narrows.

For the Karapiro–Ngarawahia reaches the models predicted continuing degradation, except for a quasi-stable period in reaches just upstream of Hamilton, due to adjustment of this reach to gravel extraction prior to 1976. The indicated average losses until 2044 were: 28 500 $m^3$/yr for Karapiro - Narrows reaches, 3 500 $m^3$/yr for Narrows-Victoria Bridge reaches and 26 800 $m^3$/yr for Victoria Bridge-Ngaruawahia reaches.

The Barnett Consultants report notes that the degradation trend since 1963 differs from that of earlier this century. They interpret Kear et al (1964) to show that since the Taupo eruption in the 2$^{nd}$ century AD, there has been aggradation in the Hamilton region at an annual rate of 1 foot per 60 years (5 mm/yr) and this rate doubled in the first half of the 20$^{th}$ century.

Discussion

The transport of sediment is complex when sediment is supply limited. In reaches through Hamilton recent deposits can be re-entrained but fresh bed material availability may be limited by scouring from the Hinuera Formation. The Barnett 1994 model did not incorporate this process and empirical studies of historical trends may give more reliable predictions of future behaviour in these reaches.

The aggradation rate of 5 mm/year over some 1800 years would indicate a bed level rise of 9 m. This is substantial but is in agreement with other findings (see section 5.8). If this is the case, changes in river course must have occurred if the underlying Hinuera Formation is now exposed in the bed.

River cross-section up-river distances in Table B2 of the Barnett Consultant's report are incorrect between cross sections 133 and 153.

## 5.3 Statement of Evidence of H.J. Freestone

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system). References in square brackets refer to evidence clause numbers.

This comprehensive study gives an analysis of flood outflows from Karapiro Dam for the period 1947–1998. For 3 hr duration data the mean annual flood is 409 $m^3/s$ [6.13]. The results indicate that there was a 24-year quiescent period from 1965–1989 with no extreme floods. Subsequently, four out of the five largest long duration floods for the 1947-98 period occurred during the 1990s. Natural storm patterns and not hydropower management caused these long floods. Hydropower influence commenced in 1929 when Arapuni Dam was commissioned and Karapiro was commissioned in 1947.

Changes in flow regime.

The Tongariro Power Development (TPD) diversions have augmented Karapiro outflow by 13% from 1979 [8.2]. Although a further 12% increase in rainfall is predicted in the next 35 years, its effect will be cancelled out by reduced runoff due to increased forestation according to Mr Freestone's evidence. The only forecast change in Waikato flows over the next 35 years is that a reduction in diverted flow from the TPD of the order of 1.3 $m^3/s$ is likely [9.14].

Mr Freestone gives a timeseries plot comparing historic Karapiro outflows with a hypothetical 'no consents' flow regime for the years 1948-2001. The 'no consents' regime displays much less flow fluctuation than actually occurred.

A comparison of past and present outflows from Karapiro is made for the period 1958-2002 (see Fig. 16 bottom, in section 6 of this report). The figure shows that prior to 1981 the common operating range was 140 $m^3/s$ to 350 $m^3/s$. From 1981-1998 the outflows fluctuated over a smaller range of flows. From 1999 onwards the size of flow fluctuations increased again to typically range from 140 $m^3/s$ to 380 $m^3/s$ or higher.

Figure 16, top, taken from Mr Freestone's evidence, shows the number of Karapiro outflow peaks above 200 $m^3/s$ for October years from 1965-2000. From 1965 through the 1970s there was an average of 1.3 peaks greater than 200 $m^3/s$ per day, with a maximum of 2.1 peaks/day in the year beginning Oct. 1966. From 1980-1998 there were fewer peaks over 200 $m^3/s$, averaging 0.6 per day. For 1999 and 2000 the number of peaks increased again to around 1.4 per day.

Changes in water level.

A comparison of water levels near Hamilton's Victoria Bridge (also called the Traffic Bridge) shows the 1921-1961 mean level was 0.9 metres higher than the 1975-2000 mean level [15.4]. The earlier record of levels shows considerable stability about the mean level while the more recent record shows a downward trend over the 25-year period [15.6]. From this we can conclude that degradation was not occurring in the 40 years prior to 1961. Rating curve data for the Victoria Bridge site have been used to produce specific gauge plots for given flows over the period 1960-2000. This record is reproduced in Figure 16, middle. The figure shows the reference water level fell about 1 metre in 16 years from 1960-1976 and a further 0.4m in the 24 years 1976-2000 [15.9].

Discussion.

It is understood that the investigation of peak frequency is made in order to indicate the degree of ramping, which occurs when Karapiro power station is operated to respond to fluctuations in electricity demand at different times of the day. The statistic of number of peaks greater than 200 $m^3/s$ per year is not necessarily a robust indicator of adverse ramping effects, as the rate of rise appears to be a more important factor. Also, a quasi-steady flow hovering about 200 $m^3/s$ could provide several peaks greater than 200 $m^3/s$ without any ramping. Frequency distributions of rates of water level rise may give a better indication of ramping effects. The ramping peak magnitude and peak duration are additional factors of interest. While the duration of ramping peaks is not investigated by Mr Freestone, the record of Karapiro discharge (Fig. 16, bottom) shows that ramping peaks since 2000 approach the 1947-98 mean annual flood level of 409 $m^3/s$.

Further discussion of Mr Freestone's data is given in the Analysis of data section.

Recommendation.

- Investigate statistics on rate of rise, duration and magnitude of ramping peaks.

## 5.4 Statement of Evidence of D.M. Hicks

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system). References in square brackets refer to evidence clause numbers.

The parts of this evidence relevant to the present study include a description of the river system, reporting on historical bed levels, sediment budgeting, and the effects of the proposed hydro operations on bed levels downstream of Karapiro.

River Description.

The Waikato R. passes out of pumice country around Karapiro and the sediment it receives from its tributaries tends to be muddier. Within the Hamilton area the river is incising into alluvial Hinuera Formation that was deposited as an alluvial fan between 12,000 and 40,000 years ago. The size of the material in this formation varies, with median sizes of samples ranging from small pebbles to silt, but typically the median sizes are coarse to very coarse sand grades. Cores near Hamilton show that these various grades are interlayered [11.21]. From Karapiro to Ngaruawahia the river gradient flattens, the river remains incised within terraces whose height above the river decreases downstream, the bed-material size reduces from gravel to coarse sand and there are relatively few sediment inputs from tributaries.

Bed levels.

Through the Hamilton area, bed levels have generally fallen quasi-steadily since the 1960's. At some sections, the fastest falls occurred in the 1960's and 1970's, coinciding with the period of gravel extraction. Bed levels continued to fall through to the early 1990's and they appeared to generally stabilise between the 1994 and 1998 surveys. Since 1998 they have fallen more rapidly. At Fairfield Bridge the minimum bed level has tended to fall more rapidly than the mean bed level [11.7].

Degradation rates seem to increase in the downstream direction and the greatest degradation tends to have occurred where the mean bed level was already low [11.9]. The apparent reduction in the degradation rate shown by the 1998 survey is attributed to the July 1998 flood, which preceded the survey. In this flood the backwater effect of the high Waipa River reduced bed shear stress downstream of the Narrows Bridge [11.10]. This effect is likely to have resulted in a temporary reversal of bed degradation downstream of the Narrows and cross-sections indicate deposition of 130 000 $m^3$ occurred in that period [11.11].

Bed level change is also investigated from flow gauging records on the assumption that water level moves with the mean bed level. This indicates 34 mm/yr of degradation at Victoria Bridge between the 1960's and 2002 [11.13]. The records show that the section at Ngaruawahia only began degrading from about 1976. This downstream delay in the onset of degradation is consistent with a downstream progressive erosion wave stemming from the sediment starvation effect of the hydro dams. [11.14].

It should be pointed out that the bed level changes inferred from gauging records in the evidence are the changes in water level that would be necessary to match the measured flow to the rating curve applicable in 1960. If the cross-section shape, bank vegetation or channel slope should have changed with time, the so-called "bed plot" will incorporate these changes. Thus, while the technique identifies changes in hydraulic regime, the magnitude of these changes may not be directly related to the amount of bed degradation.

Water records measured monthly between 1921 and 1961, at the old water treatment plant, are interpreted to show stable bed levels prior to 1960 [11.15]. Analysis of the record actually indicates a mild, long-term aggradational trend prior to 1958.

Sediment budget.

A bed-material budget is used to compare loads carried by the Waikato under natural conditions and under the present hydro-dominated conditions. The main influences on the lower river bed-material budget have been hydro operations and sand and gravel extraction [10.1]. The hydro dams have induced a deficit in supply of sediment to the lower Waikato bed amounting to about 104 000 $m^3$/yr on average since 1947 [10.10]. Around 9000 $m^3$/yr is contributed to the river between Karapiro and Ngaruawahia. Hydro control and TPD augmentation have increased bed material transport capacity by 17% at Hamilton's Victoria Bridge [10.11].

Between Karapiro and Ngaruawahia the bed material deficit is calculated to be 127 000 $m^3$/yr, largely reflecting the effect of dam entrapment [10.17]. Surveys indicate the average annual bed volume change from 1973 - 98 was 101 000 $m^3$/yr [10.8]. Thus the budgeting demonstrates that the bed level changes since the mid 1960's in the reach between Karapiro and Ngaruawahia can be accounted for largely by the river recovering from its own bed the deficit of bed material created by the hydro lakes.

From 1958 to 1976, a total of 830 000 $m^3$ of sand and gravel (46 000 $m^3$/yr) was taken from river reaches in the Hamilton area [10.14]. This also contributed to degradation in the Hamilton area, but overall effects of this extraction were subordinate to the hydro dam effect [10.19].

Armour layer development.

Bed surface surveys "consistently have shown evidence of armour development between Karapiro and Hamilton, downstream fining, and patchy exposures of Hinuera Formation" [11.22]. The March 2002 survey shows that the sediment is bimodal, having a gravel component and a sand component. Going downstream, the gravel mode becomes finer grained and less uniform, while the sand mode grows in importance [11.23]. Cobbles are prevalent at Cambridge and the coarsest fractions tend to be the most abundant with the whole bed surface relatively uniform in size. This indicates a static armour layer [11.24]. Further downstream, near the Narrows, part of the bed showed cobble armour with coarse sand over-passing along one bank. Further downstream at Hamilton's Victoria Bridge, the surface material was formed of less uniform pebbly gravel (4 to 64 mm in diameter), while sand again over-passed near one bank. By Horotiu the bed appeared as a mixture of fine gravel and coarse sand. By Ngaruawahia, the bed was all coarse sand [11.25].

From his investigations Dr Hicks has concluded that:

- Upstream from The Narrows the bed generally appears to have stabilised, at least where the bed is protected by static armouring.
- Through the Hamilton area, while there are signs of armour development in places, this does not appear to have generally evolved to a stable, static state; moreover the thin and sometimes patchy coverage of loose gravel over the Hinuera Formation suggests that the rate of degradation is being controlled more by the erosion resistance of the Hinuera material.
- Further downstream from Horotiu, where the river slope flattens and the bed material becomes predominantly sand, there is little coarse material with which to form an armour layer and so armouring will not develop, although hard substrate will still be exposed.

In interpreting these conclusions it should be born in mind that:

- The ultimate goal is stable bed levels and until cross-section surveys show that degradation has stopped, evidence of armour layers may only imply temporary protection.
- The Hinuera formation is interlayered [11.21], thus its erosion resistance could be highly variable and should be investigated further if more reliable estimates of future degradation are to be made.
- It is not specified how far downstream of Horotiu that the river slope flattens but the 265 $m^3$/s water surface profile of Fig. 25 in the evidence shows no significant change in grade between Hamilton and Ngaruawahia.

Shear stress.

Flow records from Jan 1999 to Sept 2000 are used to compare bed shear stress with threshold values for sediment entrainment. At several sections between the Narrows and Horotiu the daily shear stress fluctuations pass up and down through the entrainment threshold stress. The expectation in these cases is that the bed will be mobile more often than under steadier unregulated flows [11.32]. The situation is complicated in this area because the material being eroded from beneath the active gravel layer on the riverbed is the ancient Hinuera Formation, and it is not known how its rate of erosion is influenced by the mobility of the overlying gravel [11.33].

Dr Hicks then investigates the Barnett Consultants 1994 morphological model and notes that it did not incorporate many of the processes acting in the river along the gravel bed reaches such as armouring and hard substrate. He suggests that the 1994 model runs were never intended to predict bed levels in this reach [15.5]. His view is that estimates of future bed levels should be based on extrapolation of the long-term average trends determined from the surveys of recent decades. He considers this a conservative approach in that as the river's gradient is reduced through the degradation process, the river will slowly lose energy and so its capacity to entrain and transport bed material will wane.

However, in section [11.9], it is pointed out that mean bed levels through the Hamilton area show an overall average degradation rate of 25 mm/yr and "rates tend to increase in the downstream direction". If degradation is increasing in the downstream direction the river gradient will increase, not reduce, and the degradation will not wane.

With regard to whether daily discharge fluctuations can affect river bed erosion he states: The reach most likely to be affected is that between the Narrows and Horotiu. The situation is complicated, however, because ultimately the rate of bed degradation is controlled by the rate of down cutting into the more compact Hinuera Formation that underlies the riverbed gravels in this reach, and this cannot be predicted by physics-based formulae [16.5].

In the Hamilton area, degradation since 1973 to the present has generally shown linear trends. The degradation rates vary from section to section, but the overall average rate is about 25 mm/yr. Daily fluctuations in the discharge from Karapiro dam may have some influence on the rate of degradation at some sections in the Hamilton area, but this cannot be quantified because of insufficient knowledge of what determines the erosion rate of the compact substrate of the Hinuera Formation [17.11].

To resolve uncertainty in the role of the proposed daily discharge fluctuations on riverbed degradation rates in the Hamilton area, he recommends that the frequency of the current 10-yearly programme of cross-section surveys be increased to 3-5 yearly intervals between The Narrows and Ngaruawahia. [18.3].

The reviewer supports these conclusions and suggests that further investigations of ramping and the underlying substrate should also be carried out.

## 5.5 Statement of Evidence of J.A. McConchie

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system). References in square brackets refer to evidence clause numbers.

Geomorphology

As the Waikato River system is a "unique geomorphic system with a distinctive set of interacting processes", Dr McConchie states "this makes accurate predictions of geomorphic behaviour solely from theory and international examples difficult, if not impossible" [6.3].

He calculates a natural long-term rate of bed degradation in the Hinuera Formation at Hamilton of approximately 2-2.5 mm per year over the last 16,500 – 18,000 years. Lower terraces in Taupo Pumice Alluvium have been down cutting at a minimum average rate of approx 3.2 mm per year over the last 2000 years. [4.20]

Sediment transport.

The total theoretical bed material load able to be transported by the Waikato River at Ngaruawahia is said to have increased by 13% as a result of the TPD diversions via Lake Taupo [7.10]. The majority of this increase occurs under the flow conditions arising from electricity generation at Karapiro dam. A high degree of temporal variability in potential bed material transport occurs from year to year, largely as a function of flow conditions. A significant increase, of about 40%, in potential bed material load occurred during the 1990s as a result of conditions with higher flows and several large floods [7.10]. Changes in potential bed material load as a result of natural flow variability caused by climate (40%) are at least three times those caused by the TPD diversions [7.11].

Bank erosion.

A survey of all erosion scars greater than 3 $m^2$ in area was carried out in 1999. On average, just over 1 scar per km was located. For a short distance below Karapiro the density of scars increased slightly and this is the steepest section of the lower river [8.6]. It is concluded that the majority of the erosion scars are a result of a combination of weak material, disrupted vegetation cover, and land use related activities rather than the specific effect of hydroelectric operations [8.13].

The erosion survey was repeated in 2001. Of the 95 bank erosion scars between Karapiro dam and the Waipa-Waikato confluence in 1999, 60% were considered to have stabilised by 2001, primarily as a result of bank revegetation. Erosion had reduced or remained the same at the remaining sites. A total of 30 new erosion scars were recorded during the re-survey. Eleven of these scars were located between approximately 7 km downstream from Cambridge and Hamilton City. This was also the section of river where the proportion of recovered scars was lowest. The overall decrease in the number of bank scars was attributed to the large floods before the first survey [8.26] and no significant floods since [8.27].

Bank stability.

Bank permeabilities were measured and approximately 60% of the samples tested had permeabilities equal to, or greater than, the maximum ramping rates experienced on the river of 180 mm/hr [8.31 and Fig. 28]. As there is low permeability in cohesive and/or well cemented banks it was concluded drawdown effects from flow regulation are not likely to reduce bank stability through positive pore water pressure fluctuations at such sites [8.31].

For a comparison, ramping rates greater than 500 mm/hr are shown in Fig. 92 of Dr McConchie's evidence.

He concludes that if flow regulation is having an effect on stability, the sum of all those effects is still less than what would happen under the "no consents" regime or in fact natural conditions.

Near-bank velocities.

585 near bank velocities were measured at a number of sites including stable reaches and areas of concern. The velocities were measured at varying distances from the waters edge [9.6]. A comparison of the velocities measured at different flow conditions showed results such as median near-bank velocity halving when the flow more than doubled [9.14, 9.16], velocities directed in the upstream direction [9.15, 9.16. 9.20], median water velocity "decreasing by 100%" within 2 m of the bank [9.17] and "an increase in discharge was associated with a slight decrease in water depth close to the bank" [9.21].

Sediment entrainment.

Grain sizes were sampled at 8 locations. All indicated the presence of sand particles of varying sizes. The velocities measured close to the bank were generally found to be below the critical velocities for entrainment of sediment.

Gauging records from Victoria Bridge were interpreted to show that an increase in flow is accommodated by increasing depth and width rather than by changes in velocity. At a flow of 352 $m^3/s$ velocities were not considered sufficient to entrain 1mm sediment within 4 – 7 m of the bank.

Bed shear stresses from a 1-D hydraulic model were also investigated. No clear conclusions were made. Suspended sediment concentrations were measured and it was concluded that sediment concentrations are low and primarily controlled by bank lithology and morphology rather than flow conditions [9.45].

Cross section analysis.

From Hamilton cross sections it was deduced that reduction in river bed levels is a natural process that was occurring long before any flow regulation [10.4] and that bed degradation will slow through time and must eventually stop [10.7]. From 1973/74 to 1994 the overall median change in bed elevation was degradation of 0.8m. Between 1994 and 1998 the overall median change in bed elevation was aggradation of 0.1 m. It is concluded that at least some of the degradation is a direct consequence of sand dredging operations. Several eroding sites are described in detail and mechanisms of bank failure are discussed. Statistics on range in water levels and rates of change in water level are given for the period 1983 – 2001.

McConchie Evidence Conclusions:

- Although the bed levels in Hamilton have been reduced by up to 3 m, in places undercutting the bank and increasing the slope angle, these banks have remained stable. There is no evidence of slope instability in the past resulting from this degree of bed lowering. The effects of bed degradation on slope stability are also significantly greater than any potential effects of drawdown caused by changes to the hydroelectric operating regime [11.8].
- All the physical evidence suggests that bed degradation, and the regulation of water levels for hydroelectric generation, have not significantly reduced the stability of the river banks in this area. This opinion is said to be supported by the results of a series of slope stability models [11.9].
- There is therefore no evidence that the stability of the river banks through Hamilton will be significantly affected as a result of the hydroelectric operations. Field data and quantitative analysis of bank stability are said to support this conclusion [11.17].

**Discussion**

Dr McConchie's declaration that *because the Waikato River system is unique, prediction of geomorphic behaviour is difficult or impossible,* is not a good starting premise. The theory of sediment movement does not change for the Waikato situation and, where there are many unknown factors, international experience suggests the best approach is often an empirical one, based on known historical behaviour. If the Waikato situation is complex, an analysis should attempt to delineate any fundamental trends underlying the various processes at work in the river.

The evidence describes investigations at particular sites and draws conclusions related to local situations. It is not possible to find any common factor or trends by comparing these investigations. In some cases the methodology prevents any such comparison. This is particularly pertinent in the investigation of near-bank velocities. It is understood that velocity measurements were made at fixed distances from the water's edge, rather than at fixed locations. In addition to problems of locating the water's edge where there is bank vegetation, as flow increases, any slope of the local bank or beach necessitates these measurements being taken further from the centre of the river than at lower flows. The reviewer believes that this non-standard procedure could explain the unusual results of the velocity measurements.

While the bank erosion investigation concentrated on near-bank velocities and entrainment thresholds, the reviewer's inspection of the river revealed that while there are intermittent erosion scars, much of the bank instability arises from bank failure. This occurs simultaneously on both sides of the river in places (rather than erosion scars on the outside of curves) and general failure can be indicative of general degradation. Dense and lush bank vegetation means that failure can occur without leaving persistent bank scars.

On the basis of the field inspection it is suggested that a common mode of failure is bulk sliding by the mechanism illustrated in Fig. 13.

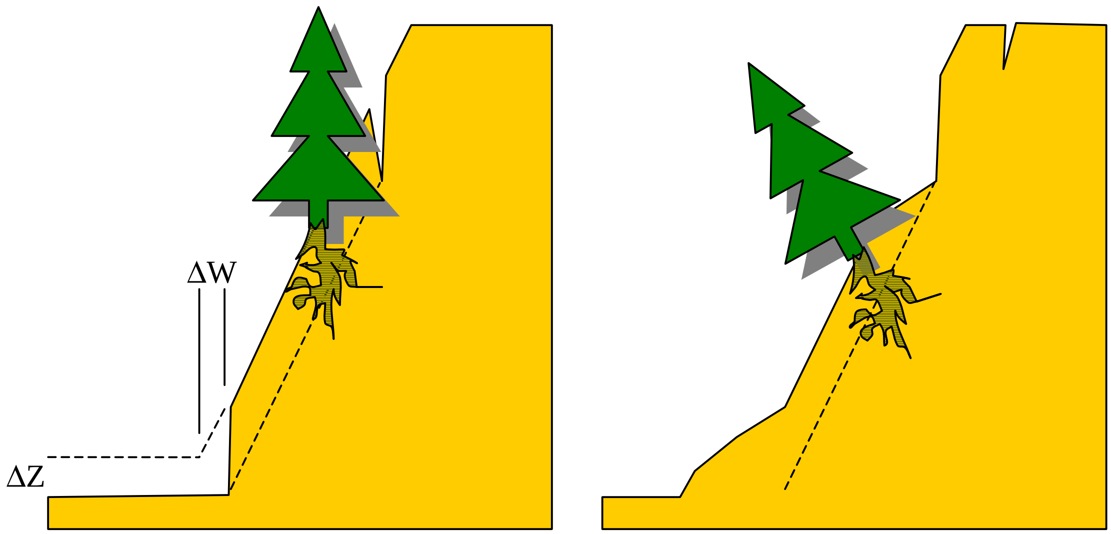


**Figure 13 Schematic representation of bank failure by bulk sliding showing: degradation ΔZ and widening ΔW (left) and situation after failure (right).**

The reviewer suggests that velocity and entrainment investigations at fixed locations on the bed of the channel may have given more consistent results and shed more light on causes of bank problems than the somewhat arbitrary near-bank measurements. In addition, the near-bank velocity measurements were not suitable for any analysis of flow turbulence.

Figures in the evidence show that the 1974 – 98 degradation rate is roughly ten times the suggested long-term natural rate. Considering that the proposed long-term rate is an average rate for a process that is diminishing with time, the resulting present natural degradation rate could be expected to be considerably lower than the long-term average rate. The apparent recent surge in degradation rate, and the fact that it commenced following completion of Karapiro Dam, should have been discussed in evidence describing the river's geomorphology. The rates of Schofield (1967) could also be investigated. They indicate that the bed has been aggrading in the vicinity of Hamilton since 130 AD.

The references to 40% flow variability attributed to climate are understood to indicate variability due to weather patterns. Mr Freeman's evidence reports that climate change may cause a 12% increase in rainfall over 35 years.

Dr McConchie's conclusion that *all physical evidence suggests that bed degradation and the regulation of water levels for hydroelectric generation have not significantly reduced the stability of the river banks in Hamilton* is contentious and, unless degradation has now stopped, his inference that this stability will continue into the future is not well justified and not consistent with the Opus (2001) bank stability report findings.

## 5.6 Statement of Evidence of M.G. Webby

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system).

Unless otherwise noted, the following text refers to the Karapiro-Ngaruawahia section of the river.

Mr Webby carried out computational hydraulic modelling of reaches of the Waikato River using recently surveyed bed topography. His simulations show flow and level fluctuations for December-May periods, when the river is usually low, and June-November periods when the river is usually higher. Dry, wet and average periods from the 1980's and 1990's were studied. Regimes resulting from typical hydro operating rules were compared with the ‘no hydro consents’ case. The results show that under the ‘no consents’ regime, water levels and flows would generally vary over a very small range on a daily basis. Under the proposed future hydro operating regime relatively large daily level and flow variations could often occur in the Waikato River below Karapiro dam [4.23].

A longitudinal profile of maximum and minimum water levels shows that, for an average December-May period, minimum levels for proposed hydro operations are lower than the ‘no consent’ minimum levels and maximum levels are higher than those for the ‘no consent’ regime. At Hamilton, for the average Dec.-May period, the range in water levels under the proposed hydro regime would be around 2.2 metres, which is double the range in levels that would have occurred with no consents. The range in simulated future river levels is greatest in wet periods and smallest in dry periods. The daily range is typically 2m at Cambridge and 1m at Hamilton.

The modelling shows that under flood conditions, Waipa River flows entering the main river at Ngaruawahia can induce a very significant backwater effect extending as far upstream as the Narrows Bridge. In the July 1998 flood the modelled backwater effect was approximately 0.5 m.

The rates of change of simulated future water levels were also investigated. Maximum rising and falling values were +1.85 m/hr and –0.95 m/hr respectively at Fergusson Bridge (7.0 km downstream of Karapiro), +0.60 m/hr and –0.30 m/hr at Narrows Bridge and +0.30 m/hr and –0.25 m/hr at Hamilton's Victoria Street Bridge [9.14]. Maximum values of daily range in water level were about 2.3 m at Fergusson Bridge in Cambridge, 1.8 m at the Narrows Bridge and 1.7 m at Hamilton's Victoria Street Bridge gauging station.

Mr Webby compares the proposed hydro management regime with historic records over the last 20 years. Fig. 14 shows statistics on these results for a river cross section immediately downstream of the Narrows Bridge. Future results are arrived at by applying the proposed hydro operating regime to historic data.

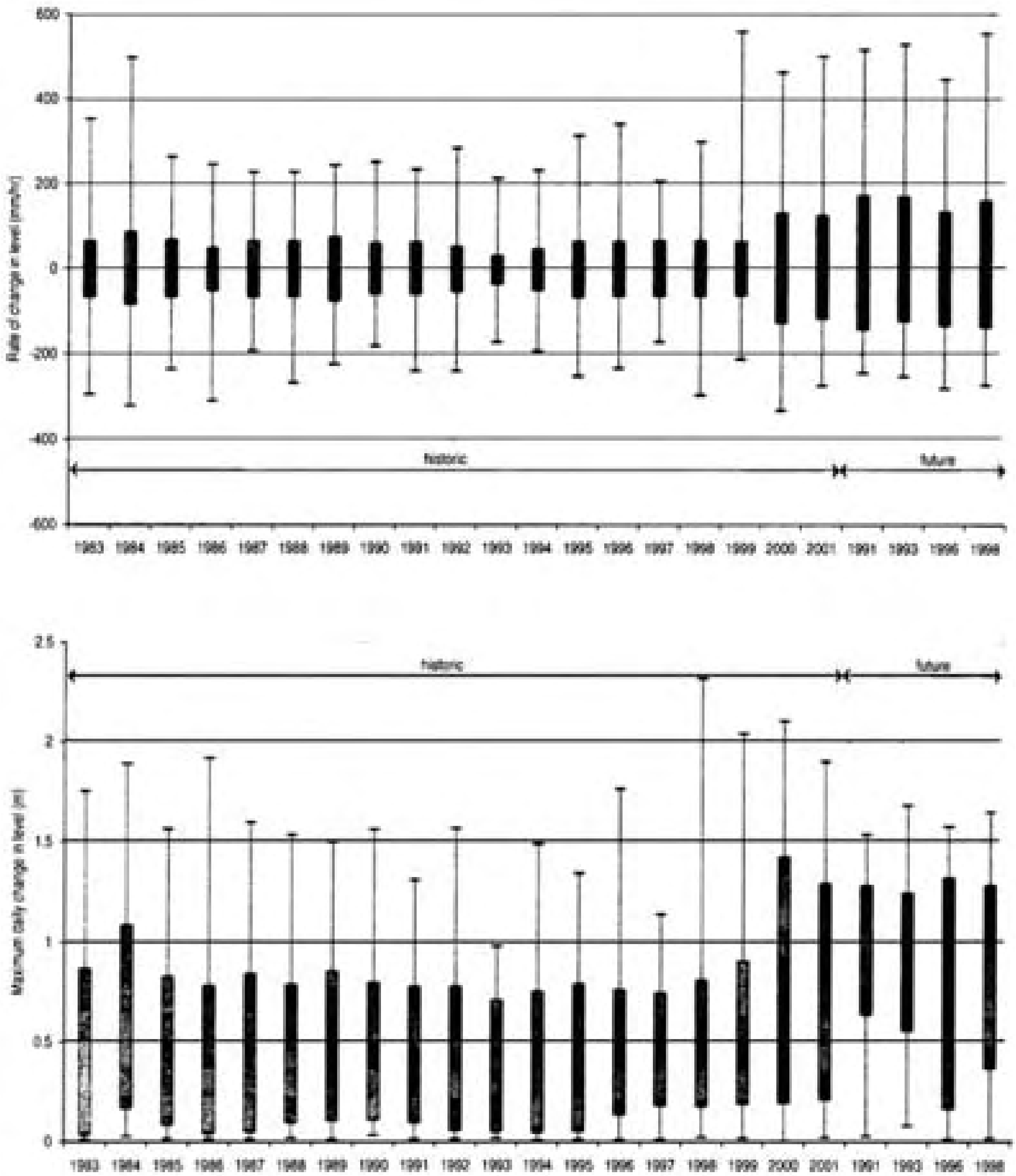


**Figure 14 Historic and future water level variation 400 m downstream of the Narrows bridge showing statistics on rates of change [mm/hr], top, and daily range [m], bottom, as projected by Webby. Whiskers show annual maximum and minimum values, boxes show values exceeded 10% and 90% of the time.**

The statistics show a distinct change commenced around 2000 when compared to previous years. This change reflects early implementation of the proposed future hydro management regime, which has increased ramping rates for outflows from Karapiro power station.

Discussion.

Mr Webby's simulations show that hydro operations increase the range of daily fluctuations in river water level and increase the rate of water level rise compared to a no consents situation. The proposed future hydro operating regime further increases these ranges and rates. The statistics on rate of change in water level could be better interpreted if rising and falling flows were analysed separately.

The maximum ramping rate of 1.85 m/hr is ten times higher than the maximum rate used for assessing bank stability in Dr McConchie's evidence ( described in section 5.5).

Mr Freestone's evidence shows that there was a higher range in operating levels prior to the period investigated by Mr Webby.

The reported backwater effect from the Waipa River during high flood conditions is likely to help reduce flood scour and erosion from Hamilton downstream. This effect also suggests that a downstream weir could be effective if remedial measures are required to counter degradation at some stage in the future.

## 5.7 Waikato River Survey Report, Horotiu Bridge to Narrows Bridge 2002.

(Basheer, G., Podrumac, B. & Lamb, R., 2002)

Surveys were undertaken in July-August 2002 to measure river cross sections between Horotiu and The Narrows. These data were over-plotted on previous survey information and mean bed levels were calculated. In comparing the 2002 cross-sections with the 1998 survey, 40 out of the 48 sections showed degradation. The mean bed level showed a similar rate of degradation for most of the cross sections and the rate was approximately 60 mm per year. The volume lost from the 25 km reach surveyed was calculated to be 116 000 $m^3$/year since 1998 and 105 000 $m^3$/year over the longer term 1986-2002.

Earlier river cross-sections shown in the report indicate degradation at the Narrows Bridge in the 1950's and degradation commencing further downstream in the 1960's.

The data and calculations appear to give an accurate assessment of recent changes in the bed. Cross section 151 in the report had an error and a corrected version is reproduced below. At this site the river is not only deepening but also narrowing. In this respect it is not typical in that narrowing sites seem to be out-numbered 2:1 by cross-sections showing widening.

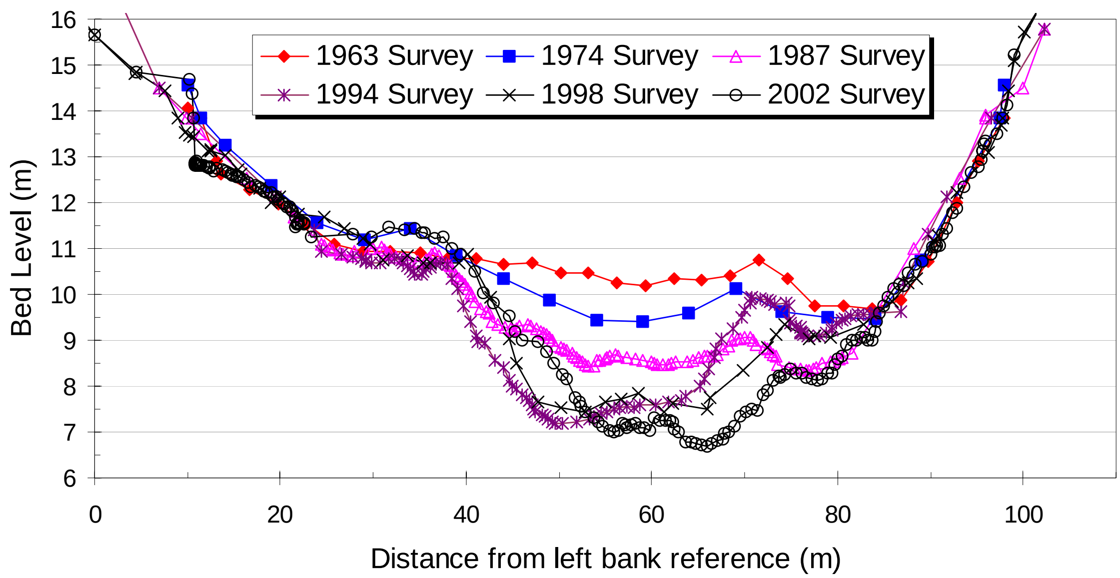


**Figure 15 Cross section 151 at Hamilton's Victoria St Bridge showing evolution over time. Vertical scale is 10 times the horizontal scale.**

## 5.8 Historic Bed Level Investigations

While the surveyed cross sections indicate degradation starting in Hamilton in the 1960's and upstream of Hamilton in the 1950's, any trends in bed level prior to construction of Karapiro are of interest.

Water level records given in Dr Hicks evidence indicate a mild aggradation trend prior to 1958. This agrees with an aggradation trend reported by Schofield (1967). He pointed out that whereas the average depth of the Waikato was 10 to 15 ft where it joins the Waipa River, the Waipa deepened from 20 – 22 ft at 300 m above the confluence to 30 – 35 ft at 800 m above the confluence and thus there has been aggradation within the Waikato 20 ft (6.2 m) greater than in the Waipa River. He studied other tributaries and concluded: "Since 130 AD the bed of the Waikato River has riven 20 to 30 ft at Huntly, Taupiri, Ngaruawahia and Karapiro". Schofield states that at the time of writing (1960's): "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 "a combination of man-made erosion and rise in sea level".

In notes to the Hamilton Geological map, N65, Kear *et al* (1964) state: "From evidence supplied by the interrelationships 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."

Notwithstanding Dr McConchie's findings, it appears that there is strong evidence of aggradation occurring in Hamilton reaches of the Waikato, prior to the effects of the hydro dams.

## 5.9 Statement of Evidence of Leroy Leach

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system).

Mr Leach reports risks to wastewater reticulation, the water supply network, bridge embankments and storm water outfalls attributable to water levels and bank instability in the Waikato River. An example is Hudson Gully, which enters the Waikato River 2.8 km upstream of the Cobham Bridge. This gully was left hanging as a result of river degradation. In 2001 the natural outflow weir collapsed and subsequent back-cuttting of the tributary resulted in serious bank collapse propagating up the gully. Remedial work had cost $260 000 to date.

## 5.10 Statement of Evidence of George Rogan

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system).

Mr Rogan addresses the potential effects on bridge foundations of ongoing reductions in bed and water levels. He tabulates pile depth, foundation description and gives cross-section drawings for each bridge between Ngaruawahia and Cambridge. He assumes an average degradation rate of 25mm per year and concludes that for decay or corrosion from wetting and drying, the only bridge that may be of concern is the Fairfield Bridge which has timber piles. Should these piles be exposed he recommends concrete encapsulation.

With regard to reduced support of piers and foundations he suggests that local flood scour may be the critical factor, rather than longer term bed lowering. For the Claudelands and Ngaruawahia Road and Rail Bridges, some of the piles could have less than the minimum embedment depth that current design techniques would require but embedment depth is considered adequate to sustain vertical loads.

With regard to lateral stability the Claudelands Bridge situation could become critical only if pile embedment depth were reduced to around 9 metres (14 metres at present).

Bank stability could potentially affect the Victoria Bridge at Cambridge, the Narrows Bridge and Hamilton's Victoria Bridge.

Mr Rogan concludes that reductions in river bed level have no significant effects on the structural performance of the bridges.

### 5.11 Other Evidence

(Applications by Mighty River Power Limited to the Waikato Regional Council for resource consents in respect of the Waikato hydro system).

The Environment Waikato Staff Report with contributions from Bruce Melville, Peter Riley and Paul Mitchell, summarises the main issues and recommends restrictions on Karapiro ramping rate. The Brief of Evidence of Nick Rogers discusses environmental effects and reviews the MRP evidence. Jarrod Bowler's evidence covers the augmentation of Waikato flow by Tongariro Power Development diversions.

## 6 Analysis of data

### 6.1 Hydraulic evidence of degradation

To reveal possible effects of floods or generation waves on degradation, three plots from the Freestone evidence are aligned in time and reproduced in Fig. 16. The top plot shows the annual number of times the flow rose above 200 $m^3/s$ and gives a crude indication of ramping. The middle plot shows when the flow rating curve had to be adjusted to respond to degradation or (in one case) aggradation. The lower plot shows Karapiro discharge.

The "peaks per annum > 200" statistic (top) has no apparent effect on the specific gauge record (middle). The first downward step in the gauge record occurred during the October 1962 flood flows (bottom graph) and the 1986 step could also be associated with moderate flood activity. At other times there is no clear link between changes at the gauging section and flood activity.

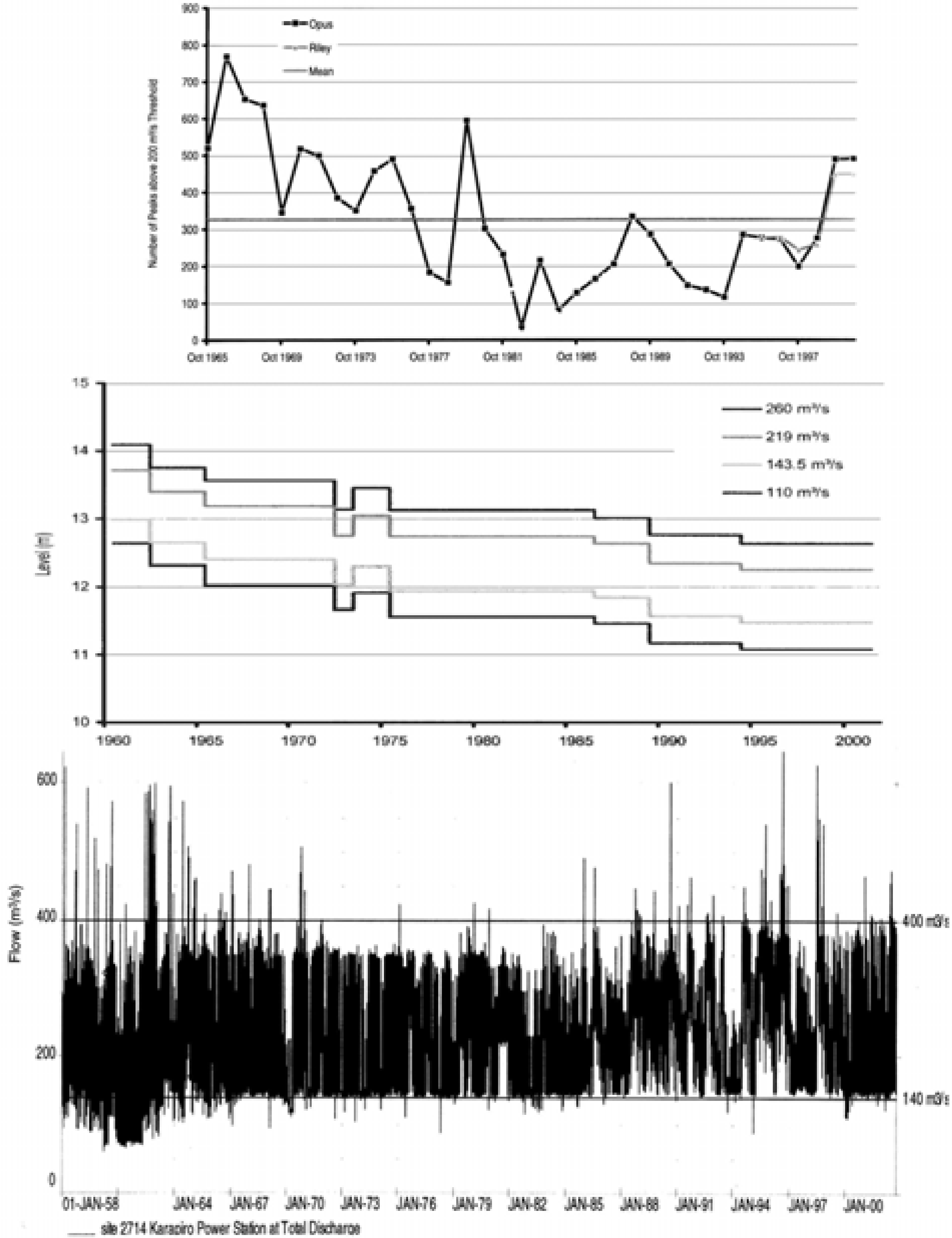


**Figure 16 Aligned time series from Freestone Evidence showing: Number of peaks per annum above 200 $m^3$/s for Karapiro half hourly outflows (top), specific gauge record for 4 flows at Hamilton's Victoria Bridge (middle) and Karapiro discharge (bottom).**

The specific gauge record is analysed in more detail in Fig. 17 and trend lines have been fitted to the mid-points of each stable step for the 260 $m^3/s$ and 110 $m^3/s$ cases.

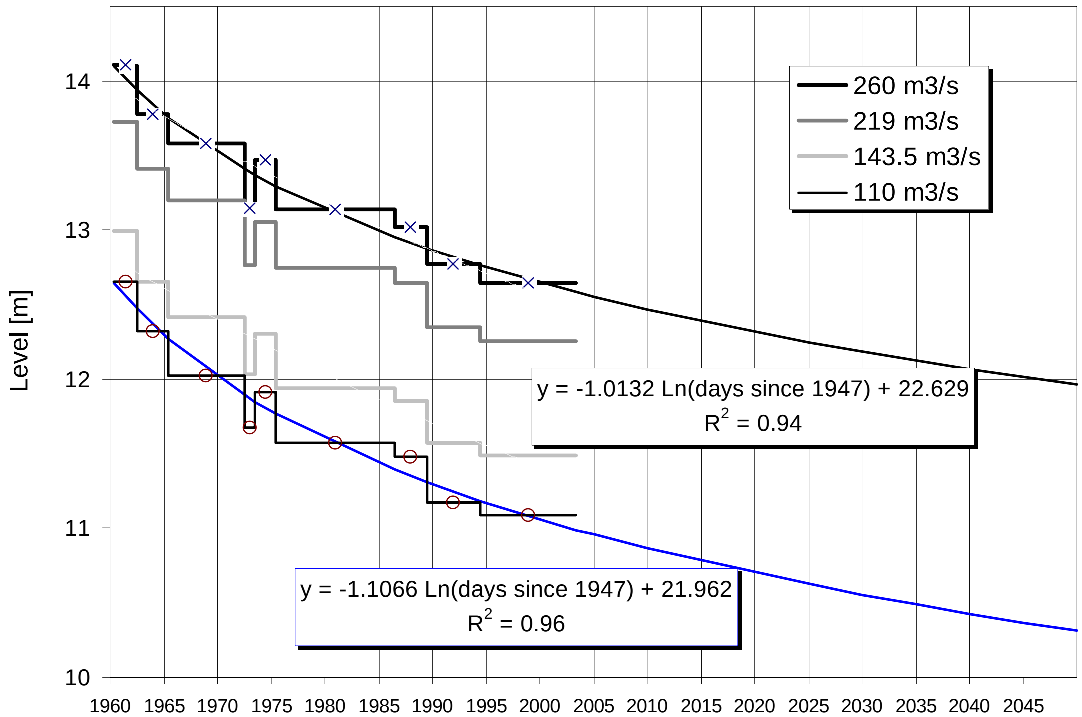


**Figure 17 Victoria Bridge specific gauge record extrapolated to 2050**

Although degradation did not affect the record until after 1960, the curves found to give the best fit to the data, have an imaginary origin in 1947, which is when Karapiro Dam was commissioned.

The step-like appearance of the record appears to indicate sudden changes in the gauging cross-section. The steps reflect the times at which the stage-discharge rating curve was adjusted. This can occur as a result of floods as noted on the previous figure or to adjust for a gradual trend. Further studies could investigate any potential link between steps in the record and rapid ramping or prolonged flows above the entrainment threshold.

A closer inspection of the most recent rating period (Fig. 18) indicates that the downward trend is still occurring within the "stable" period.

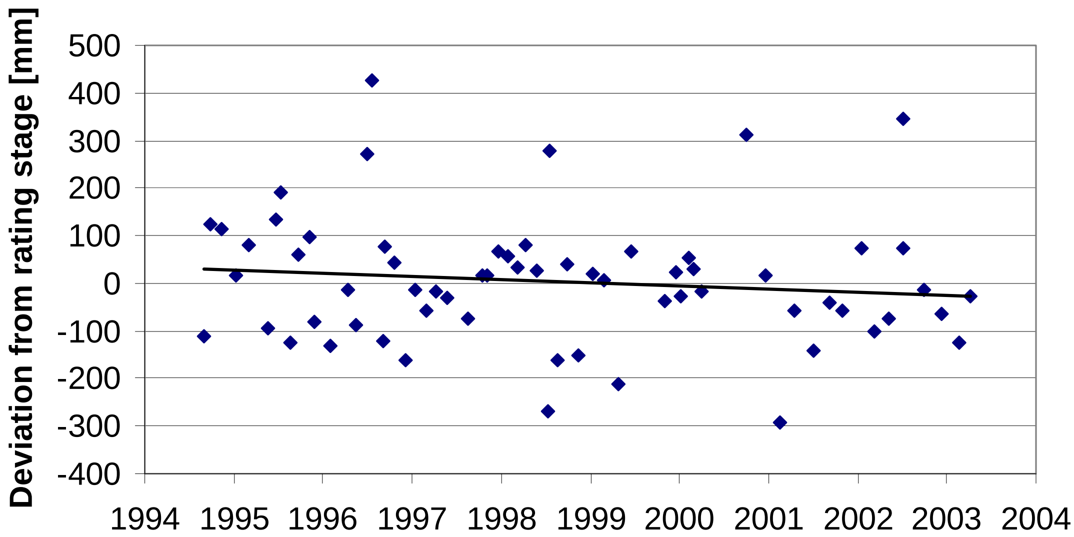


**Figure 18 Expansion of most recent "stable" rating shows degradation trend is continuing.**

The fitted curves of Fig. 17 have the property that, from 1960 onwards, annual degradation rate = $k$ /(years since 1947) where $k$ = 1.0 for the 260 $m^3/s$ curve and $k$ = 1.1 for the 110 $m^3/s$ curve. Because 260 $m^3/s$ covers more of the bed than 110 $m^3/s$, the lower degradation rate for the higher flow indicates the lower flow bed is deepening faster than the higher flow bed. From Fig. 15 it can be confirmed that the river at this section is both deepening and narrowing with time.

A comparison of present and future conditions predicted by the equations fitted to Fig. 17 is shown in Table 1.

**Table 1 Future changes at Victoria Bridge section as indicated by specific gauge method.**

| year | Rate of water level decrease | | Fall below present water level | |
|---|---|---|---|---|
| | at 110 $m^3/s$ | at 260 $m^3/s$ | at 110 $m^3/s$ | at 260 $m^3/s$ |
| 2003 | 20 mm/yr | 18 mm/yr | 0 | 0 |
| 2050 | 11 mm/yr | 10 mm/yr | 0.67 m | 0.48 m |

These mean values are based on the continuation of present trends. There is temporal variation of up to 0.25 m about the water level trend lines. Any changes in the erodability of underlying bed strata could markedly change the future trends.

## 6.2 Changes in mean bed level.

Over the last 20 years, cross sections have been measured four times at 22 cross sections that cover the river from below Horotiu Bridge, through Hamilton to above the Narrows Bridge. The mean bed level of each cross section is plotted in Fig. 19. A potential cause for concern indicated by the figure is that the lower mean bed levels have tended to fall faster than higher bed levels. While it may seem obvious that high points of the bed are more resistant to erosion, the corollary is that the lower levels are more easily eroded. As the whole bed is moving towards lower levels, it should be investigated whether the underlying strata are more susceptible to erosion than the material found at higher levels.

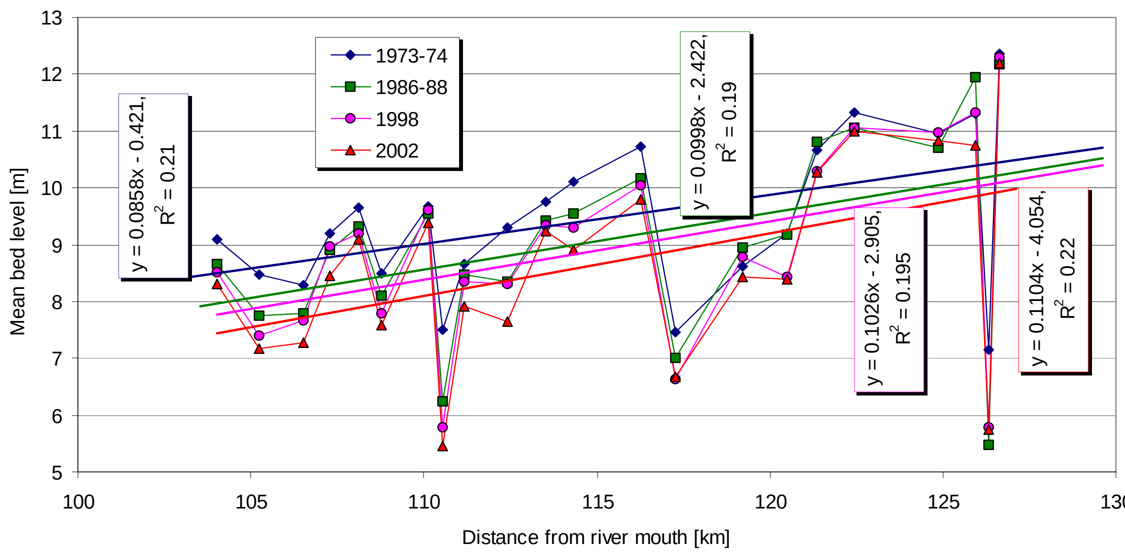


**Figure 19 Trends in mean bed level of 22 Hamilton cross-sections. Trendlines represent a plane bed smoothed of local humps and hollows.**

For each of the four surveys shown in Fig. 19 a linear trend line has been fitted. The trend lines represent where the bed would lie if it were statistically smoothed to give a flat plane. Representing the bed in this way reveals basic trends that are obscured by local variations in the bed level. What is evident from these lines is that over the years, the mean bed level of the river is not only falling but its gradient is getting steeper with time. The slope of the mean bed plane increases from 85.8 mm/km in 1973-74 to 110 mm/km in 2002. Such a trend is another cause for concern as it implies that degradation is not going to decrease through declining sediment transport capacity that accompanies a flattening bed gradient.

In the upstream direction the trend lines converge and the location of the point of convergence was investigated. The three more recent trend lines intersect the 1973-74 trend line at points which lie 142.9, 147.9 and 147.7 km from the river mouth respectively. The last points give the approximate location of Karapiro Dam. Thus the bed through Hamilton can be represented as a tilting plane with an imaginary hinge in the vicinity of Karapiro Dam.

To investigate future mean bed levels, the time evolution of the bed plane levels at Pukete Boat ramp (downstream of Hamilton) and near the Narrows Bridge (upstream of Hamilton) are shown as dotted lines on Fig. 20.

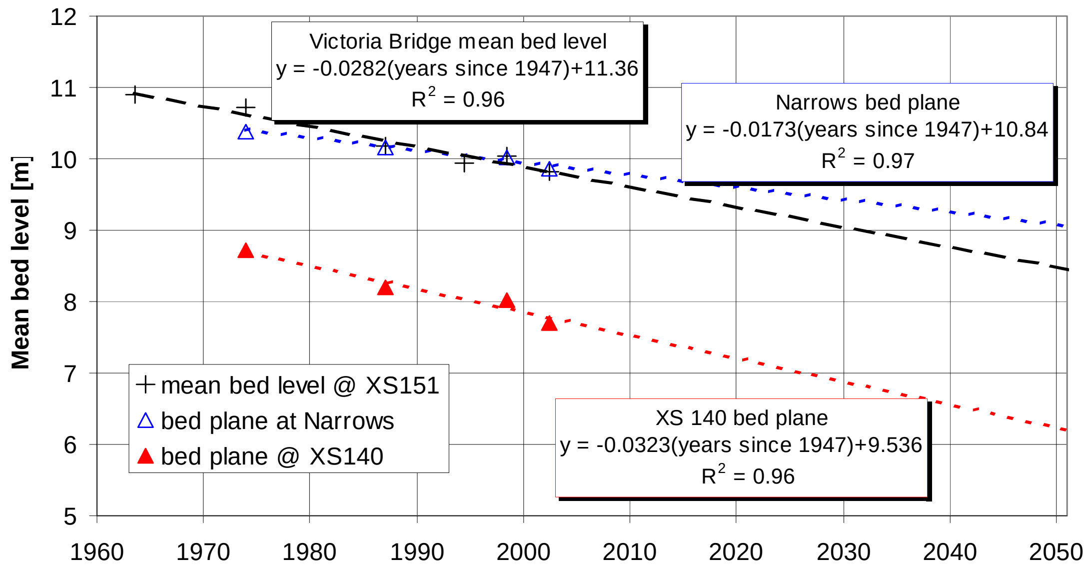


**Figure 20 Trends in mean bed level at Victoria St Bridge (XS 151) and trends in level of the bed plane at Pukete Boat Ramp (XS 140) and downstream of Narrows Bridge (km 126), extrapolated to 2050.**

It can be seen that the mean bed levels are dropping at a fairly constant rate of 32 mm/yr at XS 140 (downstream of Hamilton) and at 17 mm/yr upstream, near the Narrows. These rates and the resulting 2050 bed levels are shown in Table 2.

**Table 2 Future mean bed levels predicted by extrapolating present trends.**

| Location | Rate of fall in mean bed | Fall below present by 2050 |
|---|---|---|
| Bed plane below Narrows | 17.3 mm/yr | 0.8 m |
| Victoria Br. mean bed level | 28.2 mm/yr | 1.3 m |
| Bed plane below Hamilton (XS 140) | 32.3 mm/yr | 1.5 m |

These mean values are based on the continuation of present trends. There is local mean bed level variation of up to 4.8 m about the trend lines. In addition there is variation of several metres in cross section bed levels about the section mean bed level. As noted above, any changes in the erodability of underlying bed strata could markedly change the trends. Surveys of the sub-bed strata, evaluation of the downstream migration of degradation and future cross-section surveys will be needed to confirm or modify this extrapolation of the present data.

The deviation of mean bed levels from the bed planes are shown in Fig. 21 along with bank top width. Several features are revealed in this plot:

- Deviations are getting larger with time (unstable system).
- The lowest cross sections are falling faster than the bed plane, which is falling faster than the highest cross sections.
- In general, narrow sections have larger deviations than wider sections.
- The change in fitted trendlines could be interpreted to show that low sections will get wider with time and high sections will get narrower.

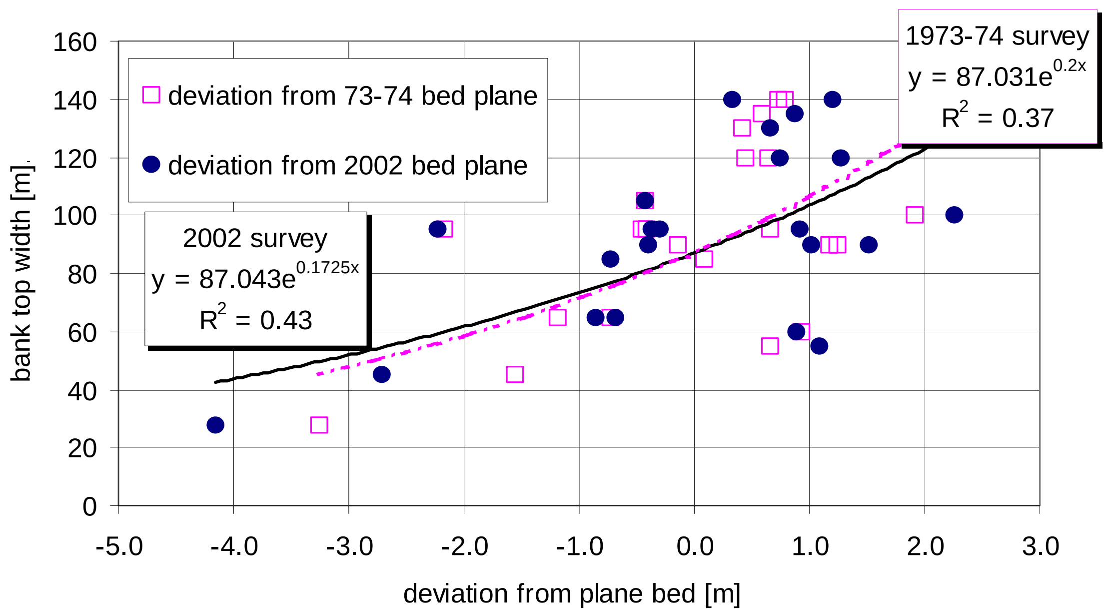


**Figure 21 Relation between bed level and bank width.**

The banktop width used here is a somewhat arbitrary measure and more precise statistics on width at a given flow could be obtained using a reference width such as surface width at mean annual flood (which could be found with a hydraulic model and historic cross section surveys). As noted above, future surveys are needed to confirm such extrapolation of statistical trends.

## 6.3 Underlying Strata

Bore logs from test bores in and near the river, provided by Hamilton City Council, show the substrate is stratified with layers containing different proportions of gravels, pumice gravels, silica sands, various grey and brown sands, silts and peat. The gravel bearing layers are generally closer to riverbed level with sediments getting finer with depth. Fig. 22 shows bore logs made under the riverbed in the vicinity of the water treatment plant, upstream of Cobham Bridge, close to river section 153A or 153B given in the Waikato River Survey Report.

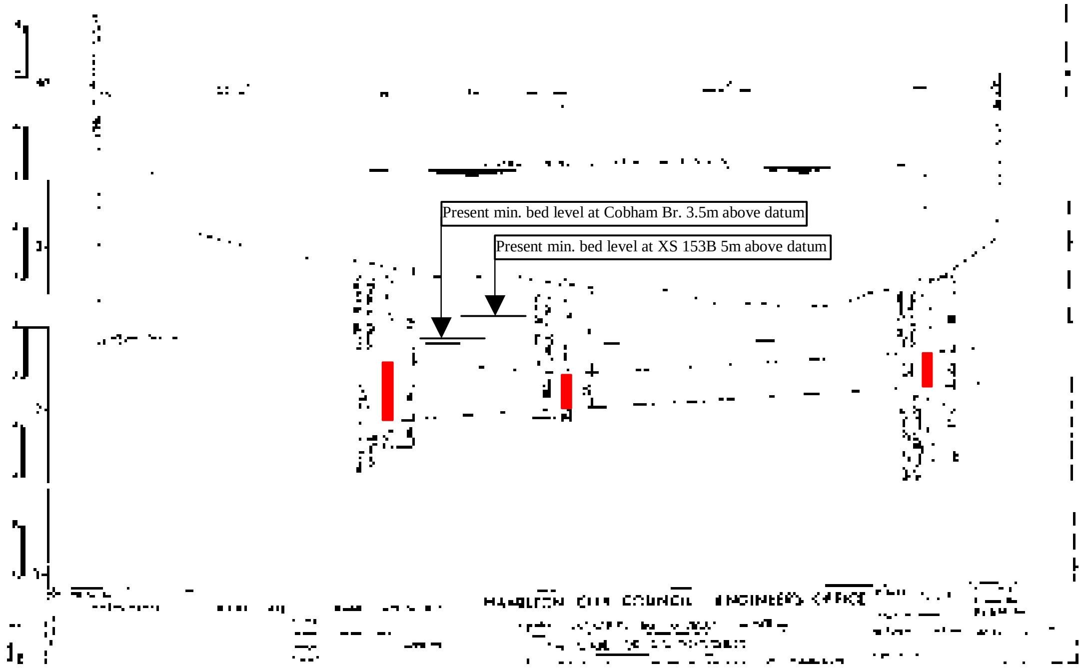


**Figure 22 Test bores for a water main crossing near the water treatment plant (near section 153 B, river km 118.8) show peat layers under the Waikato River.**

The figure indicates that there are underlying peat layers that may be within 4 m of the 1969 bed level. Note that the thickness of the peat layers is around 8m and not drawn to scale in Fig 22. Since 1969 the bed level has fallen further (minimum bed level at section 153B fell more than 1m from 1998 to 2002). The 2002 minimum bed level at sections 153 (Cobham Bridge) and 153B are indicated on Fig. 22. There may now be only around 1 – 2 m of loose gravel pumice and sand overlying the peat layer. The erosion resistance of the peat is unknown but because there is the potential for rapid degradation when the peat layer is exposed, the properties of sub-bed strata should be further investigated.

The Waikato River Survey Report (section 5.7), shows very deep holes have formed rapidly 1 km further downstream from these test bores (at cross-sections 152 and 152B). Such behaviour could be explained by erosion of a soft peat layer.

## 6.4 Bed Material Size

An important factor that can govern sediment entrainment is the size of particles on the riverbed. McCraw (1967) describes the Waikato Fan as having the common three part pattern : (a) the apex sediments which stretch from Karapiro to beyond

Cambridge and consist mainly of gravels; (b) the middle part which lies between Cambridge and Hamilton and consists of low gravel ridges separated by shallow depressions partly filled with fine sediments; (c) the toe which stretches far out into the basin beyond Hamilton and is comprised of fine sediments consisting mainly of pumices silts and sands.

Limited field data were obtained from Environment Waikato and the Barnett Consultants 1994 study. The median grain size (d50) and the 84 percentile grain size (d84) for these data are shown on Fig. 23 at sampling locations between a point 50 km from the river mouth and Karapiro Dam. Samples downstream of the Narrows Bridge were collected in 1964 and samples from the Narrows Bridge upstream were collected in 1994. One (fine grained) sample taken in the gullet is not included due to the transient nature of sediment passing through the gullet. The figure indicates an upward step in bed material size upstream of the Narrows. Cobbles and coarse gravels are found above the Narrows but not downstream. The samples confirm McCraw's description given above. There is only one sample in the degrading Hamilton reaches (103 km – 128 km from mouth) that were investigated in Fig. 19. Upstream and downstream samples indicate the median sediment size could range from just over 1mm downstream of Hamilton to just under 2mm upstream of Hamilton.

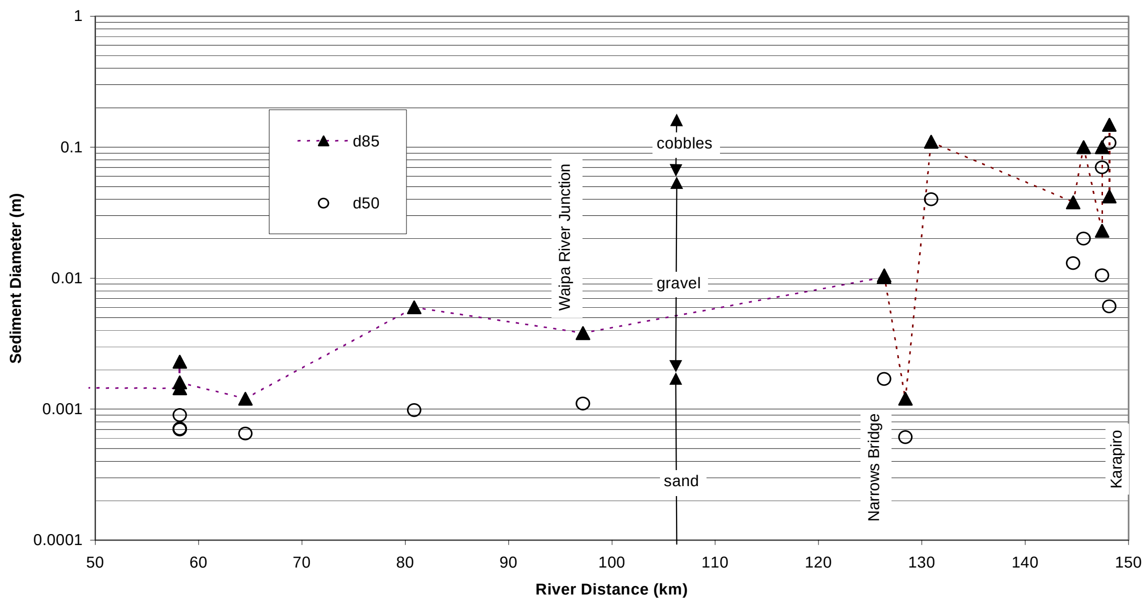


**Figure 23 Sediment sizes measured along the Waikato.**

### 6.5 Significance of Ramping

A down-slope force balance for one-dimensional unsteady open channel flow with a hydrostatic pressure distribution is:

$$\tau_o = \rho\, h\left[g\; S_o - g\frac{\partial h}{\partial x} - \frac{\partial V}{\partial t} - V\frac{\partial V}{\partial x}\right] \tag{1}$$

In Equation 1, $\tau_o$ is bed shear stress, $\rho$ is water density, $h$ is the water depth, $g$ is gravitational acceleration, $S_o$ the bed slope, $V$ the cross-sectional average velocity, $x$ is the downstream distance, and $t$ is time. Terms in the square brackets represent gravity, pressure, acceleration and momentum forces respectively. The last three of these terms can be produced by flow changes such as ramping. As no measurements of the spatial derivatives are available, it is necessary to transform Equation 1 by replacing spatial derivatives with temporal ones. This is achieved by considering an observer moving with the wave, and assuming that such an observer would not see any flow variation (Henderson, 1966):

$$\frac{\partial h}{\partial x} = -\frac{dt}{dx}\frac{\partial h}{\partial t} = -\frac{1}{C}\frac{\partial h}{\partial t} \tag{2}$$

where $C$ is the wave celerity. While no specific measurements are available, data from the reports can be used to make an estimate of the different terms in Eq. (1). The following assumed values are used for a hypothetical cross-section towards the upstream end of Hamilton:

$V$ = 1.3 m/s, $h$ = 4.5 m, $\delta h/\delta t$ = 560 mm/hr (Fig. 14), $C$ = 8 m/s, $S_o$ = 0.0001 and with these assumptions the terms in the square brackets of Eq. (1) become gravity: 0.001 N/kg,   pressure: 0.0002 N/kg,   other terms: negligible.

For a steady, uniform flow, only the gravity term would produce bed shear stress. Thus, these very rough estimates show that pressure effects from ramping could potentially increase bed shear stress by around 20%. Field measurements during ramping should be made to verify these provisional indications. The effect of turbulence on sediment entrainment could also be investigated as part of the field measurements.

### 6.6 Discussion of analyses

The mean bed level and specific gauge records both indicate that degradation is an on-going process but they appear to imply different rates for future degradation. At Victoria St. Bridge, past trends indicate that by 2050 the mean bed level will fall, at a steady rate, to around 1.33 metres below its present position. The specific gauge record indicates water levels will drop at a decreasing rate and the low water level will fall by only 0.67 metres at the same site in the same period (i.e. the fall in mean bed level is double the fall in water level). Which indicator of degradation is more accurate? As both methods are robust and based on reliable and reasonably accurate data, the question arises as to whether both predictions could be correct. i.e. are there conditions that could allow the water level to fall more slowly than the bed level? The first possibility is that high, erosion resistant bed sills are controlling the water level at the Victoria Bridge site. Fig. 20 indicates that mean bed level at the site is falling steadily at 28.2 mm/yr and Fig 19 shows no high points within 5 km in the downstream direction. A hydrographical survey would expose any undetected sills in the riverbed and hydraulic modelling could reveal any backwater effect of downstream high points. Any sills found to be controlling water levels should be surveyed by core boring to locate underlying weak layers.

A second possibility that would allow water level to fall more slowly than mean bed level could be that average water velocity is decreasing at the gauging site. Factors that could cause velocity to decrease would be an increase in the channel bed or bank roughness or a decrease in bed slope. Bed roughness could increase due to larger sized bed particles or larger bed-forms developing. There have been suggestions that there is evidence of bed armouring in the vicinity of Hamilton but the steady fall in mean bed level precludes the existence of any enduring armour layer. Growing bed forms are not expected or reported and, consequently, an increase in bed roughness is worth investigating but probably unlikely. Bank roughness may have increased somewhat due to vegetation and slumping effects. On the other hand, Fig. 19 shows that the average channel slope is steadily increasing. Thus, while worth investigating, there is no obvious reason to suspect that average water velocities are decreasing. The matter could be resolved by using historic gauging data to examine the evolution over time of area of flow for a specified flow.

The third possibility that would allow water level to fall more slowly than mean bed level would be if the average channel width is increasing over the reach of river that influences water levels at this site. The way in which mean bed level is evaluated between fixed points means that if the channel is widened inside these points, the actual channel depth must be reduced to maintain the same mean bed level. If sufficient historical survey data were available, this could be investigated by studying the evolution over time of surface width for a specified flow. Given the bank movement reported in the field inspection and the number of widening cross sections noted in section 5.7, it is feasible that river widening is taking place.

### 6.7 Accuracy of predictions

While the trend lines of water surface levels in Fig. 17 and mean bed levels in Fig. 20 have a very good fit (around 95% of the variance in historic data is explained) it would not be prudent to use these data to fix error bands on future predictions. Although historical trends are internationally recommended as the best way to predict future trends, such predictions rely on the continuation of the historical rates of change.

For the Waikato situation there are four main factors that could alter future rates of change. Firstly, gravel extraction has influenced the historical data but should not occur again in the future, secondly, there is no guarantee that the historical composition of the bed substrate is representative of what will be encountered in future, thirdly, there is evidence that the river has started widening and finally, any effect of ramping on entrainment has not yet been quantified.

The gravel extraction and river widening effects will tend to make the forecasts conservative, i.e. actual degradation should be less that predicted by extrapolation. Substrate changes and increased ramping may cause under prediction of future bed levels. Further investigations of substrate and ramping are recommended.

Until such effects are quantified it is proposed that the trend lines should not be extended beyond the 50 year period shown.

# 7 Recommended Further Investigations

**Morphology** (Approximate cost of these morphological analyses excluding monitoring and surveys is $25K. $40K if a new hydraulic model set-up is required).

- Investigate any trend in flow area, over the years, at a given flow and investigate the influence of sills. Confirm preliminary indications that the river channel is widening by looking for trends in water surface width at given flows. Use gauging records or hydraulic modeling to reveal whether any changes in river velocity or roughness are occurring with time or whether it is solely the erosion resistant sills that govern changes in the specific gauge record.

- Extend recent cross section surveys to cover all reaches between Ngaruawahia and Karapiro so that the analyses applied to the Hamilton reaches can be extended upstream and downstream.

- Using the above information and substrate results (below), extrapolate degradation rates to predict bed levels in 50 and 100 years time.

- Regular monitoring of bed cross-sections should be carried out.

- Future developments in morphological models may allow investigation of the effects on degradation of different flow and ramping scenarios. (This option is not included in the above costing).

**Geotechnical**

- Survey a longitudinal thalweg profile to identify the locations of erosion resistant sills. (Approx. cost $10K for simple sounding, $42K for a sub-bed seismic survey and side-scan sonar or swath bathymetry).

- Investigate bed substrate density and strength properties to a depth of at least 3m below the present thalweg at critical locations and near erosion resistant sills. (Approx. cost $10K per location).
- Calculate bank stability at degrading locations where failure could be hazardous. (Approx. cost $2K).

**Ramping**

- Investigate statistics on rate of rise, duration and magnitude of ramping peaks. (Approx. cost $20K using existing water level data).
- Measure bedload transport rate and flow turbulence during typical and extreme ramping conditions. Compare critical shear stress and sediment concentration with rate of change in water level and flow turbulence. Evaluate the findings in light of the above ramping statistics. (Approx. cost $80K for 3 monitoring sites).

# 8 Conclusions

There is widespread acceptance that degradation is a typical consequence of dam construction. Usually the degradation reduces with time and a quasi-stable bed should eventually establish. The Karapiro – Ngaruawahia reaches of the Waikato River show signs of active degradation, especially between Cambridge and Horotiu. The fall in mean bed levels does not appear to be reducing with time.

The primary cause of the degradation is the hydro dams that cut off sediment supply from upstream. Degradation was aggravated by sand extraction in the past.

Measurements of degradation trends are obscured by areal and temporal variations in the river bed. Removing local variations shows mean bed levels through Hamilton follow a sloping plane. The slope of the plane is getting steeper with time. Long-term bed plane level is falling steadily at approx 32 mm/year just downstream of Hamilton and at 17 mm/year just upstream of Hamilton. There is no evidence of any decrease in this rate. Deviations of mean bed level about the plane are getting larger with time. Extrapolating the plane in the upstream direction shows that its origin (or hinge) lies in the vicinity of Karapiro Dam.

Within Hamilton, water levels are not falling as fast as the mean bed level and the rate of water level fall is decreasing. The Victoria Bridge water levels are falling by around 20 mm/year in 2003 and extrapolating trends shows water levels could be falling at around 11 mm/year in 2050. The difference between the steady fall in mean bed level and a decreasing rate of fall in water level can be explained if there are hard sills governing water level or if the river is widening.

Two potentially serious situations could develop:

- Degradation may produce a situation of critical bank stability, which causes a river to switch from deepening to widening,
- Weaker layers may exist below the river bed and cause a sudden increase in degradation when the layers are exposed.

In addition, as erosion can be promoted by flow surges, measurements during ramping are necessary to establish whether the present peak load hydro generation rules are accelerating degradation.

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