Environment Bay of Plenty
REGIONAL COUNCIL

Fluvial Processes Report for the Whakatane and Whirinaki Rivers

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Environment Bay of Plenty
Operations Publication 2006/01
January 2006

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ISSN 1176 - 5550

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Preface

A draft of this "Fluvial Processes – Whakatane and Whirinaki Rivers" report was prepared in 2001 by Pascal Balley. The report followed the format and methods of Gary Williams, who had undertaken such analyses for several other rivers in New Zealand. The report also drew upon and updated a previous report by Ross Titchmarsh on the Whakatane River. Plans of the design river meander pattern in the mid reaches of the Whakatane River prepared by Titchmarsh are still relevant and should be referred to (Plans W449 and W451).

The draft from 2001 has been reviewed by Phil Wallace in 2004. Gary Williams gave further guidance on the sediment transport rate calculations.

Apart from corrections to calculations in Chapter 7, carried out by Ingrid Pak, no significant changes have been made to the 2001 draft.

Acknowledgements

Efforts in data collection and sampling by Peter Vercoe and Bradon Rowson are acknowledged, as is guidance from Phil Wallace and Peter Blackwood.

Cover Photo: Whakatane River

Executive Summary

Environment Bay of Plenty has carried out investigations into the river characteristics and sedimentation processes of the Whakatane and Whirinaki Rivers as part of the process of developing floodplain management strategies. The primary focus was a sedimentation study. However, investigations on the river characteristics have been carried out as part of understanding the sediment transport processes. The objectives of the river characteristics study were to obtain an understanding of the fluvial geomorphology of the Whakatane and Whirinaki Rivers, assessing their natural conditions and responses, and hence obtain appropriate design information. The objectives of the sediment transport study were to obtain an understanding of sediment transport in the upper Whakatane and the Whirinaki Rivers and to develop a sediment budget.

The nature of the Whakatane and Whirinaki Rivers, their rate of change and their response to flood events and management are described in Chapter 3. Both rivers are gravel-bearing rivers and rise in steep greywacke country ranges. They are contained within rugged hill country over most of their length, before crossing relatively narrow alluvial valleys. Along the study reach the rivers' gradients gradually flatten before adapting to alluvial plain conditions.

Riverbed materials were sampled and analysed for both rivers. The analysis shows that the materials sampled for both rivers were generally well graded, round greywacke alluvium with particle sizes ranging from 0.1mm (sand) to 150mm and 100mm (very coarse gravel) for the Whirinaki and Whakatane Rivers respectively. The percentage of sand of the riverbed material sampled was less than 20% by weight.

Relationships between river channel erosion and river channel meander width and patterns were investigated. It is common practice in river engineering in New Zealand to use a series of empirical formulae (Henderson, Chang, Lacey and Russian formulae) to design river channels, where extensive bank erosion and/or aggradation have been observed, to a new "design meander width and pattern" at which it is believed the channel can maintain a dynamic equilibrium. The current Whakatane River channel meander width and pattern concept is the so-called narrow managed fairway, and was adopted after a study conducted in 1992 by Titchmarsh (Titchmarsh, 1992). It has worked with some successes. The same concept is proposed for the Whirinaki River. However to avoid on-going lateral erosion, bed deepening, and shifting as in the Whakatane River (see section 4.3.3), it is proposed that the design channel widths, beside being able to fit into the natural channel widths and meander pattern of the river, must be selected to represent the largest values derived from all the empirical formulae (especially Henderson and Chang) associated with the narrow managed fairway. Buffer zones of at least as wide as 30m are recommended on both sides of the channel and within the design fairway to minimise bank erosion.

Sediment transport in a river is a function of the river channel resistance to flow. From this study (Chapter 6) it is concluded that most of both rivers' channel resistance to flow arises from grain roughness, with the energy of the river flows being dissipated almost entirely on sediment transport. This finding is valuable since when estimating the transport of bed material in a channel, the available energy is proportioned according to the ratio of the grain roughness to the total roughness of the channel.

A set of commonly used empirical sediment transport formulae (Meyer-Peter & Muller, Engelund & Hansen, and Einstein & Brown formulae) were used to derive, for both rivers, bedload transport equations, which are functions of flow. These equations were used to estimate an average annual bedload transport for each of the two rivers. These values were in turn

compared to the estimated annual bed volume changes in the rivers. Conclusions were then drawn that on average the annual bed load transport is 44,000m^3/year for the Whakatane River and 23,000m^3/year for the Whirinaki River.

The derived bedload transport estimator for the Whakatane River is the average of the following formulae:

For 95m^3/s ≤ Q ≤ 550m^3/s:

- Meyer-Peter & Muller: $Y = 5 \times 10^{-11} \times Q^3 - 3 \times 10^{-7} \times Q^2 + 0.0008 \times Q - 0.0764$
- Engelund & Hansen: $Y = 2 \times 10^{-11} \times Q^3 - 2 \times 10^{-8} \times Q^2 + 0.0002 \times Q - 0.0123$
- Einstein & Brown: $Y = -1 \times 10^{-11} \times Q^3 + 7 \times 10^{-8} \times Q^2 + 0.0002 \times Q - 0.0189$

For Q ≥ 550m^3/s:

- Meyer-Peter & Muller: $Y = 0.0011Q^{0.8947}$
- Engelund & Hansen: $Y = 0.00006Q^{1.1626}$
- Einstein & Brown: $Y = 0.00005Q^{1.2446}$

Where *Y* and *Q* are in m^3/s.

The derived bedload transport estimator for the Whirinaki River is:

For 25m^3/s ≤ Q ≤ 120m^3/s:

- Engelund & Hansen: $Y = -6 \times 10^{-10} \times Q^3 + 6 \times 10^{-7} \times Q^2 + 0.0002 \times Q - 0.0022$

For Q ≥ 120m^3/s:

- Engelund & Hansen: $Y = 0.00004Q^{1.3634}$

Where *Y* and *Q* are in m^3/s.

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Chapter 1: Introduction

Environment Bay of Plenty has carried out investigations into the river characteristics and sedimentation processes of the Whakatane and Whirinaki Rivers as part of the process of developing floodplain management strategies. The primary focus was a sedimentation study. However, investigations on the river characteristics have been carried out as part of understanding the sedimentation processes. The objectives of the river characteristics study were to obtain an understanding of the fluvial geomorphology of the Whakatane and Whirinaki Rivers, assessing their natural conditions and responses, and hence obtain appropriate design information. The objectives of the sedimentation study were to obtain an understanding of sediment transport in the upper Whakatane and the Whirinaki rivers. Bed material of gravel rivers is generally characterised by a wide range of particle sizes. This study seeks to review the transport characteristics of these graded sediments and to develop a sediment budget. The purpose of the exercise is to set sustainable gravel extraction rates and to effectively maintain river protection schemes of the above named rivers.

Information required to carry out the study was obtained from various sources and included channel survey data and river plans, and aerial photography taken at different times. The hydraulic modelling data were obtained for the Whakatane River from a river model calibrated on the July 1998 flood data. No flood data (debris or silt marks) were collected on the Whirinaki River and therefore its hydraulic data are estimations only. Other valuable information has been obtained from the Whakatane and Rangitaiki River Major Scheme reports.

Chapter 2: Catchment and Main Channel

2.1 Whakatane River

The Whakatane River comprises three main reaches, the upper, middle, and lower reaches with the Upper reach taken to be the reach within the ranges (refer Figure 1 and Drawing W469 in Appendix 1). The middle reach stretches from upstream of Ruatoki (9.0 km upstream of the Ohotu Bridge) where the river leaves the ranges to just upstream of the Pekatahi Bridge at cross-section 27, while downstream of the Pekatahi Bridge to the sea is the lower reach. The Whakatane River up to its confluence with the Waimana River drains 1100km^2 relatively narrow and extensively bush-covered catchment and extends 112km (see NZMS 260 Map W15 to W18 (Robertson, 1988, 1990, 1994, 1996) and Figure 1). The upper catchment tributaries to the river are short and steep, draining extensively bush-covered catchments.

The river rises in the Huiarau Ranges with an average upper catchment elevation of 1060m with a maximum of 1390m (see NZMS 260 Map W15 to W18 (Robertson, 1988, 1990, 1994, 1996)). The river quickly drops into a deeply incised valley with no river flat, with the exception of rolling lands at Ruatahuna, for the next 64km until it flows out of the main range at the upper Ruatoki Valley. At this point the valley floor widens out to an average width of 1600 metres with the surrounding hills becoming more subdued at an average elevation of 450m. Below this and for the next 6.5km the river has developed a wide meander belt with considerable areas of shingle bed and marginal river flats. At the same time, the catchment cover changes from the dense indigenous forest of the ranges (incorporating the Urewera National Park) to the scrub and grasslands of the fore hills.

Below the Ohotu Bridge, which is 32.6 km upstream of the sea, the river is generally more confined due to the establishment of willow edge protection until it reaches the confluence with the Waimana River where it adapts downstream to the sea level control. From the confluence with the Waimana River, the river continues for another 3.5km before it reaches the Pekatahi Bridge and downstream of the bridge the river is stop banked.

On its upper reach the river remains relatively steep, with a change in grade at about Ohotu Bridge, and then again at the Waimana River confluence. Upstream of Ruatoki the river channel is naturally more mobile, with adaptability to the alluvial plain condition. Downstream of Ruatoki there is a more defined and slower river channel.

Climate wise, the catchment has a northerly aspect and is not subjected to heavy rainfall from the south and west. Average annual rainfall varies from 1140mm at the coast to over 2030mm in the upper catchment and most of this rainfall occurs during the passage of frontal depressions or tropical cyclones.

The underlying rock foundation over the whole area is greywacke, which was laid down in the Permian to early Cretaceous periods. However, the catchment is in the influence of widespread volcanic activity that has induced the overlying of the greywacke base rock by successive ash mantles. This mantle is generally of shallow depth in the upper catchment where the steep slopes assist erosion of the combination of greywacke and volcanic ash layer if the indigenous forest is removed or when it is in degenerated condition. Toward the coast the mantle is relatively deep.

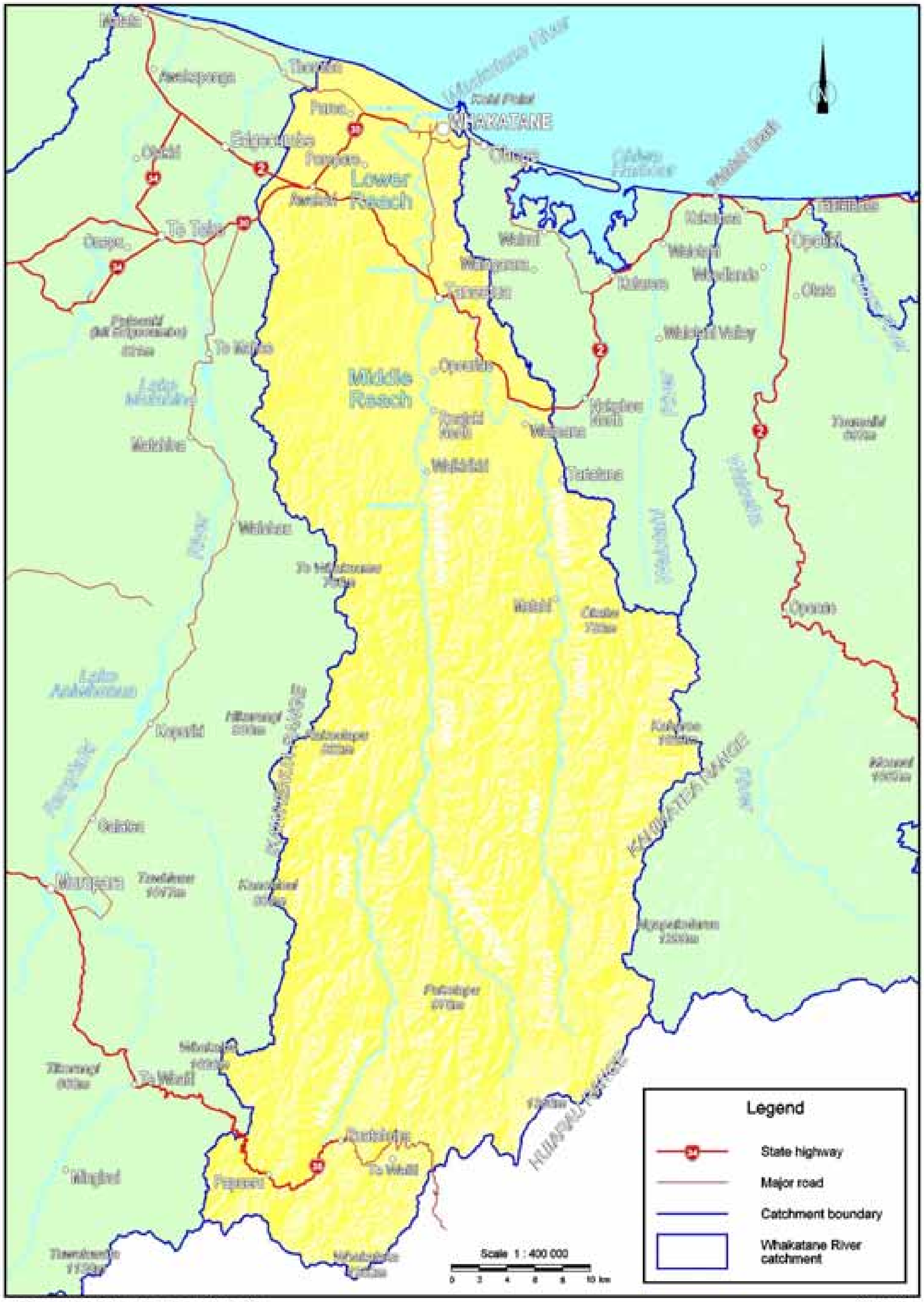

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Figure 1 Whakatane River and Catchment

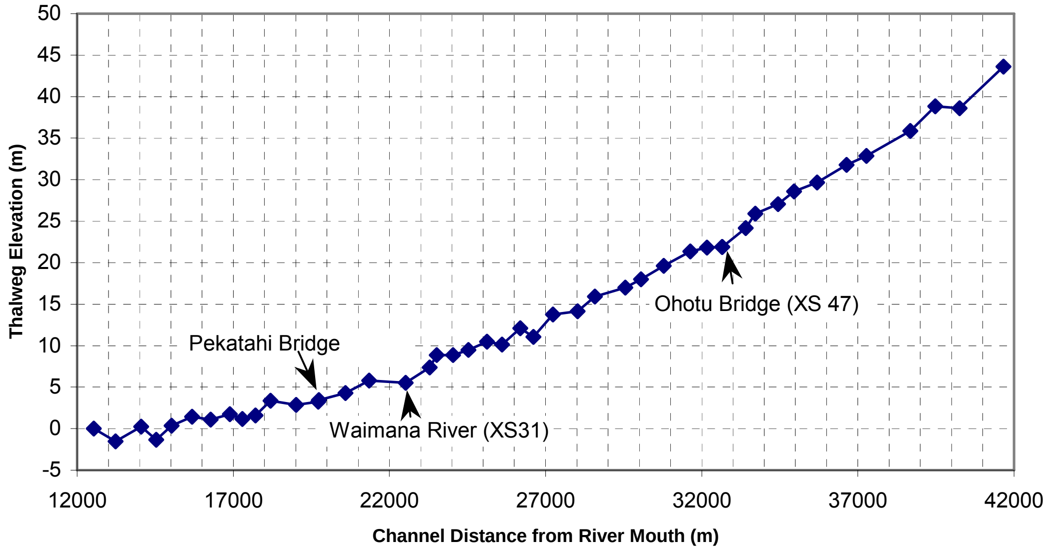

Figure 2 Thalweg gradient of the middle reach of the Whakatane River

Along the foothills and lower rangeland forest clearing and milling have taken place in the past. However, as part of the Whakatane River Major Scheme requirement and in an effort to slow down erosion, milling operation has ceased. The cleared land has now been converted into radiata pine plantations.

In spite of the rugged and steep topography and relative weathered and fractured nature of the base rock of the upper catchment there is, at present, relatively little active erosion. Most of the erosion is along the narrow gorge waterway or on some of the steepest tributary waterways. The visual impression from an aerial inspection (May 2000) was that there were many more healed or vegetating slips than bare ones. Whilst in some healed and vegetating old slips renewed slipping was observed, there are no new major slips.

Although at present there are very few active slips in the upper catchment, major slope failures are likely to occur during extreme storm events, with further period of erosion activity and waterway accumulation and reworking (erosion and deposition) being initiated. Severe earthquakes in the upper catchment could also trigger major landslides with the damming of the river in its narrow valley or of its tributaries. The potential slipping with blockage and bursting that might take place during a severe storm event or an earthquake in the upper catchment would affect the runoff characteristics of the entire catchment. The peak flood flow of large events thus will be higher than is predicted from an extrapolation from recorded small and medium sized events.

The Whakatane River runs along the Whakatane fault, which cuts north and south along the Huiarau Range and the presence of crushed zone has a significant bearing on erosion in the upper catchment. The river leaves the ranges, some 18km upstream of its confluence with the Waimana River, at a grade of around 0.0022 (m/m). The confluence of the Whakatane River with the Waimana River is located 22.515km upstream of the Whakatane River mouth (see Figure 1). The grade changes to around 0.0017 downstream of the Ohotu Bridge, also known as the Ruatoki Bridge (located 32.65km upstream of the Whakatane River mouth), before changing again to around 0.0007 downstream of the Whakatane River's confluence with the Waimana River. On leaving the ranges the river flows across a relatively narrow alluvial valley and adapts to the sea level control downstream of its confluence with the Waimana River at the flatter grade of 0.0007 (m/m). There is an observed marked reduction in flood grade of around

0.003 where the Ohotu Bridge crosses the river, with the bed gradient changing just downstream of the bridge, but with the change in the flood gradient taking place upstream of the bridge. The same phenomenon happens at the Pekatahi Bridge (located approximately 20km upstream of the Whakatane River mouth), but with a flatter flood level gradient. The difference in slope of flood level gradient between the two bridges is due to the sharp constriction at the Ohotu Bridge.

A design fairway channel, within which the river would be managed on leaving the ranges, was proposed as part of the original scheme proposals, and the more recent Middle Reaches Investigations (Titchmarsh, 1992). This fairway had a constant width and smooth alignment and is to contain the active channel reworking with buffer zones of primarily willow vegetation on either side.

This fairway approach has generally been implemented upstream of Ruatoki. The main channel in that reach of the river is maintained within a trained fairway through some substantial river training works consisting of “layering” of willows on the river margins. The layering of willow results in low growth habit of the willow, thus providing protection down at the water level where it is required. It also enhances reinforcement of the riverbank as the trees proceed to set roots along the trunks where contact is made with the soil.

Downstream of Ruatoki the somewhat slowly migrating river channel is naturally closer to a single thread channel with alternating beaches, and actual river management has been aimed at developing and maintaining willow margin vegetation.

The lower reach of the river (downstream of the Pekatahi Bridge) is stop banked.

2.2 Whirinaki River

To write for your reader, you need as much information as you can get. For legislation, demographic information about average age, gender, race, education and social status of the target group is likely to be relevant and obtainable. For environmental planning documents, you need to know how much previous reading your public are likely to have done and how well they are likely to understand the aims of your regional council.

The Whirinaki River drains a relatively narrow and extensively bush-covered catchment of 534km^2 before flowing into the Rangitaiki River (on the eastern side of the Rangitaiki River) at around 1.5km downstream of Murupara (Figure 3). The river rises in the steep Huiarau Ranges where runoff is high and consequently contributes relatively large flood flows and quantities of shingle to the Rangitaiki River.

The Whirinaki catchment is mainly steep with the river quickly dropping into a deeply incised valley (gorges and narrow gullies) with no river flat, with the exception of rolling lands at Minginui, until it flows out of the main range at the Murupara Valley. The bulk of the catchment is composed of greywacke, which was laid down in the Permian to early Cretaceous periods. However, the catchment is in the influence of widespread volcanic activity that has induced the overlying of the greywacke base rock by successive ash mantles. This mantle is generally of shallow depth in the upper catchment where the steep slopes are likely to assist erosion.

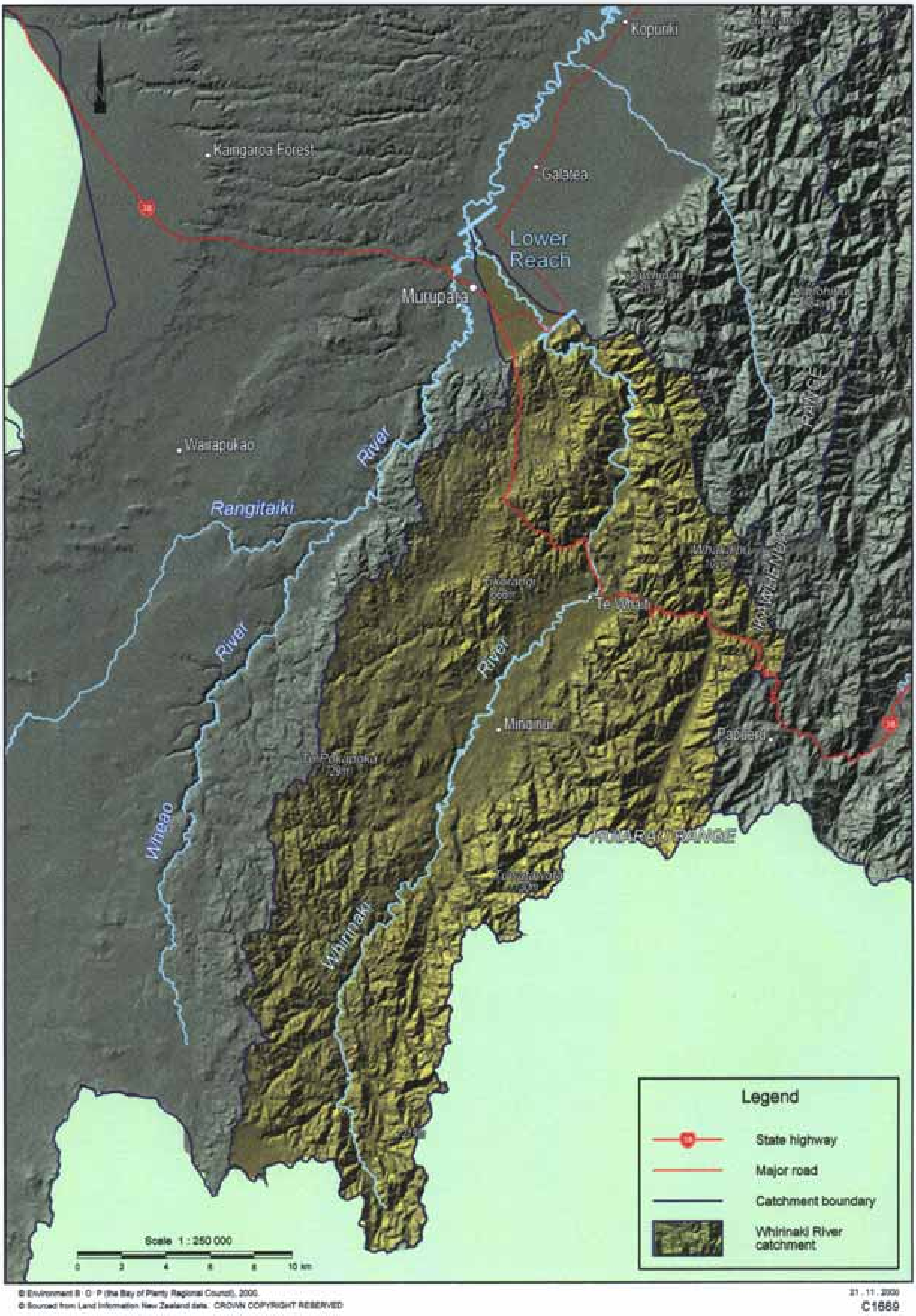

Figure 3 Whirinaki River and Catchment

Normal weathering from frost action, water erosion and wind will supply a certain amount of greywacke to the streams but the major sources are from mass movement of the hillsides which occurs during heavy and prolonged rainfall. This is due to the limited capacity of the thin layer of mantle to absorb runoff after prolonged rainfall, thus resulting in saturation of the catchment and mass movement of the steep slopes.

From 1958 through to 1970 a series of floods brought down large quantities of debris, greywacke gravel (shingle), and soil causing flooding problems, and channel instability. The shingles were fed from numerous slips, which occurred in the Huiarau ranges due to poor quality forest cover, which had been heavily destroyed by deer and possums. The vegetative cover has improved after a restoration programme, which includes the control of noxious animals. Re-growth of native trees has occurred and slip faces have been colonised by bracken and other shrub species with some evidence of regeneration of hardwood species.

There are very few active slips in the upper catchment. However, major slope failures are likely to occur during extreme storm events, with further period of erosion activity and waterway accumulation and reworking (erosion and deposition) being initiated. Severe earthquakes in the upper catchment could also trigger major landslides with the damming of the river in its narrow valley or of its tributaries. The potential slipping with blockage and bursting that might take place during a severe storm event or earthquake in the upper catchment would affect the runoff characteristics of the entire catchment.

The riverbanks are infested with overgrown willow and other vegetation such as poplar that are now in places being cleared. There are also existence of broom and other plant pests. In many places the fairway has vegetation growing on it, which traps debris during flood events creating problems. The movement of gravel is also a concern.

On leaving the range the river flattens to around 0.0033 m/m (Figure 4) and flows across an alluvial plain before joining the Rangitaiki River.

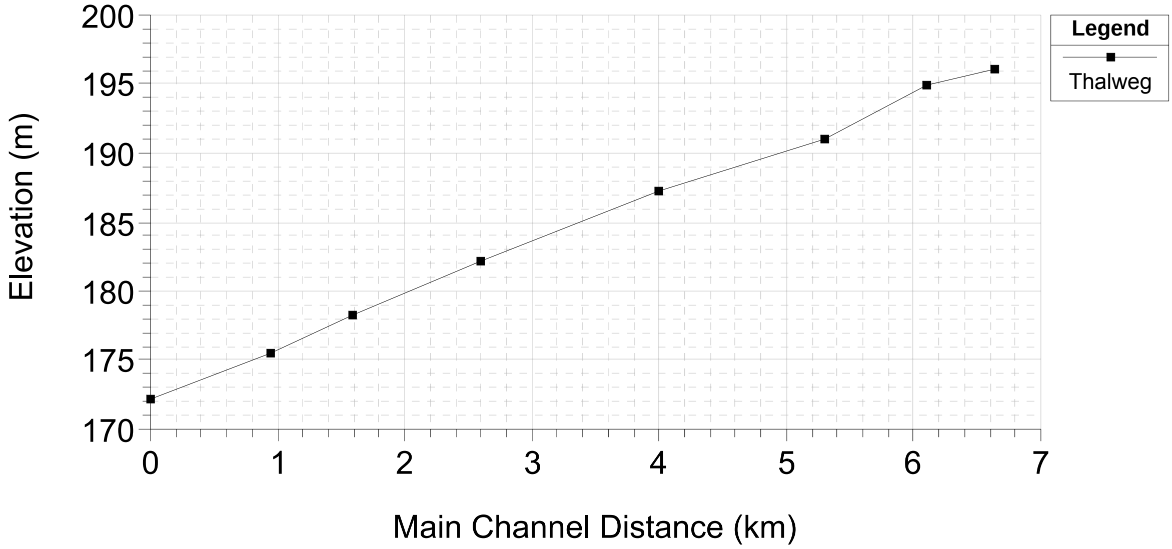

Figure 4 Thalweg gradient of the lower reach of the Whirinaki River

Chapter 3: Channel Changes

The nature of the river, the rate of change over time and the responses of the river to flood events and management are most clearly shown by the series of aerial photographs. A commentary is given below.

The aerial photographs available on the Whakatane River are taken in 1945, 1962, 1966, 1977, 1984, 1996, June and July 1998. Those available on the Whirinaki catchment are taken in 1941, 1952, 1978, 1994, 1997, and 1999.

3.1 Whakatane River

The first available aerial photographs of the middle reach were taken in 1945. The photos show a semi-braided to braided channel, with alternate channels and broken up form upstream of Ruatoki. The channel form is more poorly defined at the head of the Ruatoki valley, with virtually no tree vegetation along the river. From the Ohotu Bridge downstream, where there is a change of grade, there is a semi-braided transition with a main low flow channel, wide gravel beaches and some sub-channels. Downstream of about cross section W43 the channel becomes well formed with relatively small alternating beaches. Along that stretch there is some riverside willow vegetation. Upstream of the Waimana confluence and beside the western hills there is a meandering channel with wide gravel beaches.

The aerial photographs of 1962 show the same broken up semi-braided form with alternate channels upstream of Ruatoki, however the channels were in quite different places to the 1945 photographs. Below the grade change at downstream of Ohotu Bridge the channel has become narrower with a more uniform alternating beach form, except for a distorted bend at cross section 43. Between cross section 42 and 39 the channel is similar to that of 1945, but a more continuous margin of willow vegetation has developed. Downstream beside the western hills a much narrow channel with alternating beaches has been developed with margins of willow.

Despite the two floods of 1964 and 1965, the 1966 photographs show basically no major changes in the overall river channel arrangement, but only some shift in the main flow channel with a downstream migration of the channel upstream of Ruatoki. Downstream of Ruatoki there was virtually no change in the river channel or banks, even at the distorted bend at cross-section 43. The meander pattern of channel and beach position remains largely the same with no evidence of any significant bank erosion. The only notable change is at the Waimana confluence, where the build up of a deposition fan on the Whakatane River had encouraged a tight downstream bend. Some shingle extraction has started as shown by the extraction stockpile at the Pekatahi Bridge with the main extraction likely to be downstream of the bridge.

Between 1966 and 1977 there was a moderate flood event in 1967 and a series of events in 1970 to 1971. The shingle extraction records show an increase in extraction mainly after the 1970/1971 flood events. The gravel extraction operation around the Pekatahi Bridge is clearly evident with distorted beaches and disrupted meander pattern upstream. A small stockpile site is visible at the Waimana confluence, with noticeable change in the channel upstream of the extraction site.

The 1977 photographs show that upstream of Ruatoki the river channel has been substantially managed. The channel is generally straighter and without large bends as compared to the 1966 channel. There is evidence of strip vegetation established generally well back from the active channel. Downstream of Ohotu Bridge a better channel form had been established with no distortion around cross section 43. There is also evidence of spreading of margin vegetation downstream of cross section 42 with some narrowing of the active channel and vegetating of beaches.

On the 1984 photographs the overall channel pattern upstream of Ruatoki is similar to that in the 1977 photography although the channels themselves are quite mobile. The only striking change was the formation of a large bend that has extended beyond the strip vegetation at the site. An increase in willow plantation and the spreading of willow, especially over the upper part of the reach is noticeable. Downstream of the grade change (downstream of Ohotu Bridge) at Ruatoki two significant erosion embayments at bends have emerged, with the first one on the left bank at cross section 44 and the second on the right bank at around cross section 42. Shingle extraction is evident at and upstream of the Waimana confluence. Also evident are bank protection works, channel distortions and shifts in the meander pattern.

The 1996 photography shows an increase in plantings and spreading of willows upstream of Ruatoki, especially along the lower part of the reach. Along the upper part of the reach there has been some clearance of vegetation for farm use, including old strip plantations. The channel has a mobile semi-braided form, with some training groynes visible at bends. With the exception of the stretch of the river immediately upstream of Ruatoki, there is a good overall alignment of the river. Downstream of Ruatoki and of the grade change the channel is relatively straight with minimal beaches. Between cross sections 42 to 39 further encroachment of vegetation into the beaches has emerged. Most of the older willow trees have been removed, with some zones of younger willow plantings. Some bank erosions are evident at cross section 41 and tightening of bend has occurred at cross section 41. The gravel extraction operation at and upstream of the Waimana confluence is clearly evident. The channel meander pattern upstream of the Waimana confluence, beside the western hills, is the reverse of that of 1984.

The June 1998 river channel shows virtually no change to that in the 1996 photography, even upstream of Ruatoki.

The 1998 photographs were taken right after the large flood of July 1998. The flood has given rise to some breaking up of the main channel and wash out of beach vegetation upstream of Ruatoki. Some channel migration has occurred thus giving rise to a sequence of beach build up and minor bank erosion. Downstream of Ohotu Bridge there were some changes in the beaches, but no substantial changes in the river channel. The only significant changes were from a sequence of bank erosion embayments associated with a channel shift along the segment of the river between cross sections 42 and 39. Upstream of the Waimana confluence some reforming of beaches and bank erosion, where the meander pattern had shifted, had occurred.

3.2 Whirinaki River

The first available aerial photographs of the lower reach were taken in the 1941. The photographs show a single meandering to a semi-braided river channel. There is virtually little vegetation on the river margins or congesting the river fairway. Immediately upstream of the river confluence with the Rangitaiki River (cross section 1), there is a semi-braided transition with wide gravel beaches and some vegetation to the true left of the Whirinaki River.

The 1952 aerial photographs show the river meanders in quite different places to the 1941 photographs. Immediately downstream of the bridge (between the bridge and cross section 5) the pronounced semi-braided channel observed in the 1941 photographs reverts to a single thread meandering channel where the meander wavelengths are stretched but mobile. Between cross sections 5 and 6, the river has cut a new single channel and the wide semi-braided channel has moved to immediately downstream of cross section 5 where it is broken into three channels before reverting into a single thread channel after a short distance. Between cross sections 4 and 5 the meanders become narrower and there is formation of larger gravel beaches. The river that stretch has shifted more towards the true right bank. The shifting and narrowing trends of the meanders continue downstream of cross section 4 couple with the appearance of wider gravel beaches. Downstream of cross section 1 the braiding gives way to an accentuated meandering (small meander radius). There is also evidence of shifting of the confluence of the Rangitaiki and Whirinaki downstream of the Rangitaiki River.

The 1978 photographs show an infestation of the river margins with willow and other vegetation such as poplar, broom and other plants pests. The overall channel pattern is similar to that of 1952 although the channel itself is quite mobile. The only striking change, apart from the vegetation, was the easing of the meanders' radius of curvature between cross sections 4 and 5, and 2 and 3. Also evident is the formation, immediately upstream of cross section 1,of an island encroached by vegetation. However, there is a good overall alignment of the river with evidence of some bank erosions upstream of cross sections 6 and 4. There is also evidence of gravel extraction at cross section 6.

The 1994 photographs show an increase in the spreading of willow along the margins of the river with encroachment into the gravel beaches. The river meandering pattern is quite similar to that of 1978, but narrower due to the spreading of vegetation along the banks of the river.

The 1997 photographs show the removal of some vegetation on the true right bank at cross section 7 and the formation of a large shingle beach immediately upstream of cross section 5. There is evidence of channel braiding at cross section 7.

The 1999 photographs show similar river characteristics and vegetation infestation as the 1997 photographs with the only exception of some vegetation clearings on the true right bank of cross section 3. The lower reach of the river at its confluence with the Rangitaiki River was not flown in 1999.

In the year 2000, the Environment Bay of Plenty Rivers and Drainage Section undertook the removal of the margin vegetation along both banks of the lower reach (downstream of the bridge) of the river. The willow, poplar and other pest vegetation have been cleared to a large extent.

Chapter 4: Channel Characteristics

4.1 Empirical Meander Formulae

The rate of movement of the meandering channel is not easily quantified, as it is influenced by several factors, including bank protection works, bank strength, channel gradient, bed material size, the frequency and size of flood events and the presence of natural "hard points" such as hill toes. A variety of empirical formulae have been developed to assess the natural form of rivers under regime condition. These empirical formulae have unfortunately been derived from measurements in laboratory and on rivers with different characteristics and therefore do not always give consistent results. Where the derivation of the formulae has been guided by theoretical considerations a variety of approaches have been used with the same main aim to define channels that are hydraulically efficient and effective in transporting loose material. The result is the derivation of some measurable parameters of flow, sediment size and channel slope, with river channel width, depth and sediment load.

The empirical formulae are not able to define the plan configuration of the river channel. This is because, although, the width of the channel can be related to the radius of curvature of the meandering channel and to the meander wavelength, the proportion of one to the other depends on the type of channel. One general standard used to determine the radius of curvature is to take 2 to 3 times the meander width, whereas, the wavelength of the meander is assumed to be around 7 to 11 times the meander width. A river channel can be wide and shallow with different sized channels forming within the actively worked area of loose bed material. It can also be narrow and deep with well-formed banks and bed, which maintain their general shape as material is moved down the channel. The channel type is probably a function of the relative erodability and transportability of bank material compared to bed material, and to the balance between the available energy from flow and the expenditure of energy on the transport of sediment derived from either catchment erosion or channel reworking.

4.2 Channel Bed Material

Two different methods were used to determine bed material size for the Whakatane and Whirinaki Rivers.

For the Whirinaki River two types of gravel samples were collected from the whole of the active bed. One sample is the armouring layer of bed material and the other sample represents the whole of the bed material characteristic. For the armouring layer of bed material an area of fully worked armouring material was selected subjectively at an established river crossing, and everything within a 0.5m^2 hoop to the underside of the surface stones was collected. Then, below that armouring layer, everything to a depth of 0.3m to 0.5m was collected. To represent the whole of the active bed, 3 additional samples were collected along the line (same established river crossing) across the river channel giving 5 samples in all. The three extra samples were taken to a depth of 0.3m from the surface down. The samples were graded using standard sieves. The grading curves representative of the whole of the bed were obtained by averaging the five collected samples. The samples were taken at established river cross sections.

Due to recent willow trees clearing work on the Whirinaki River there was disturbance of the river beach around cross-section 4. Consequently no sampling of the armouring layer was done at that location.

A previous study carried out for the middle reach of the Whakatane River (Titchmarsh, 1992) used a different sampling technique. At each established river crossing a subjective sampling site was selected and everything within a $0.5m^2$ hoop to a depth of 0.3 of a metre was collected. The samples were graded using a standard sieve. The results of the sampling are adopted in this study.

The materials sampled for both rivers were generally well graded, rounded greywacke alluvium with particle sizes ranging from 0.1mm (sand) to 150mm and 100mm (very coarse gravel) for the Whirinaki and Whakatane Rivers respectively. Generally the amount of sand was less than 20% by weight. The results of the gravel grading are stored in Figures 5 to 7 and Tables 2 and 3.

Often the general relationships below are adopted for gravel bed rivers materials.

- Armouring layer $d_{25} \leftrightarrow$ whole of bed d_{50}
- Armouring layer $d_{50} \leftrightarrow$ whole of bed d_{75}
- Armouring layer $d_{75} \leftrightarrow$ whole of bed d_{90}

This relationship (especially the armouring layer d_{50} = whole of bed d_{75}) was, to some extent, validated for the Whirinaki River material. In a previous Bay of Plenty Regional Council Technical Report (Report No. 36, File 5540 WO3) by Titchmarsh (1992) the assumption that the armouring layer d_{50} equals the whole of bed d_{75} was used for the Whakatane River. Due to the lack of armouring layer sampling on the Whakatane River this general relationship was accepted as adequate and adopted in this study for the Whakatane River.

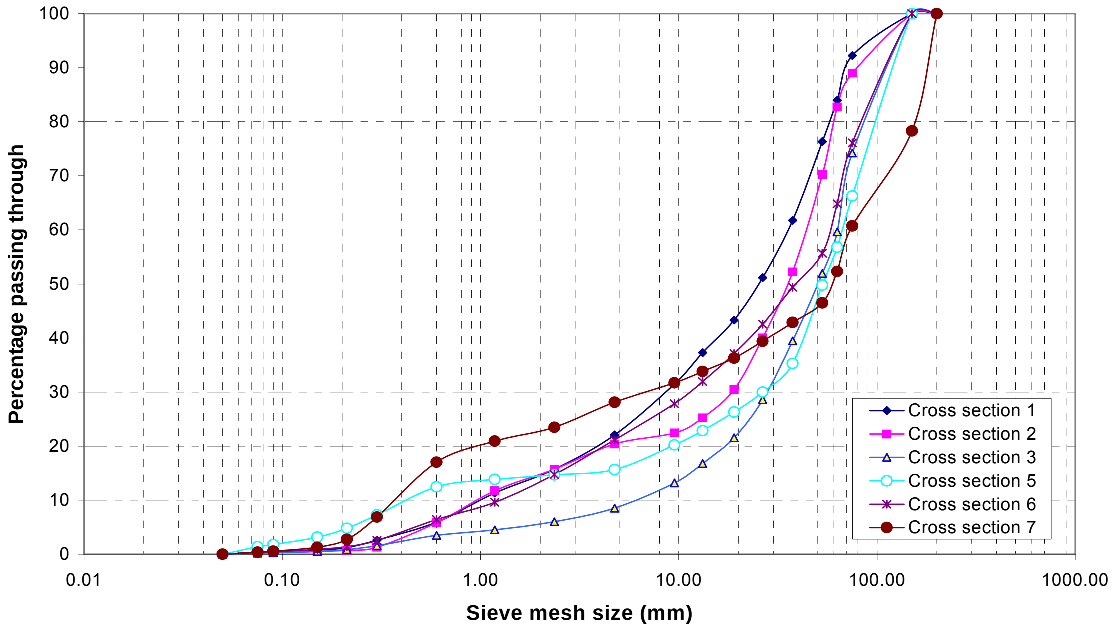

Figure 5 Whirinaki River Gravel Bed Material – Armouring Layer

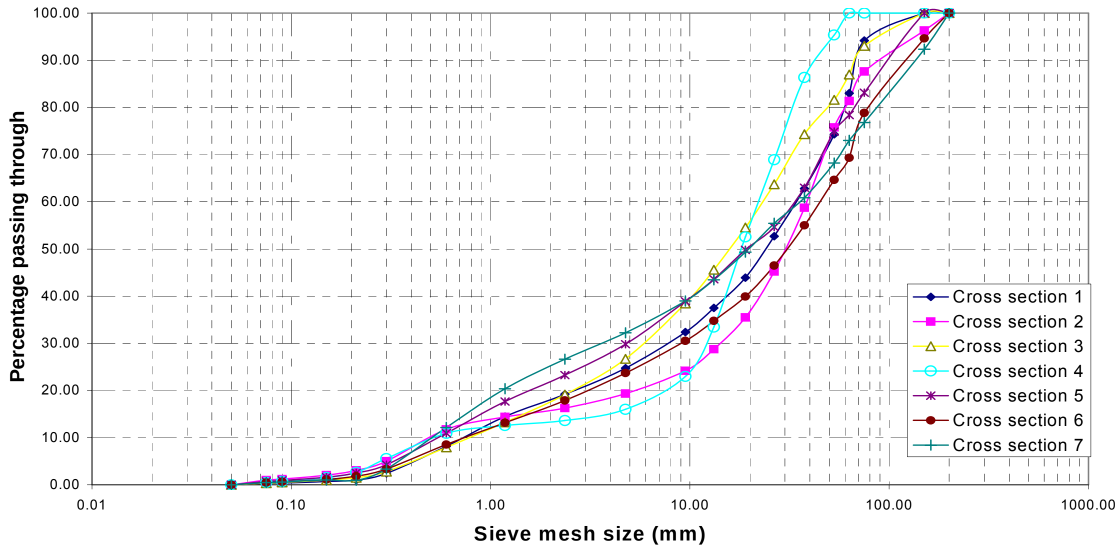

Figure 6 Whirinaki River Gravel Bed Material – Whole of Bed

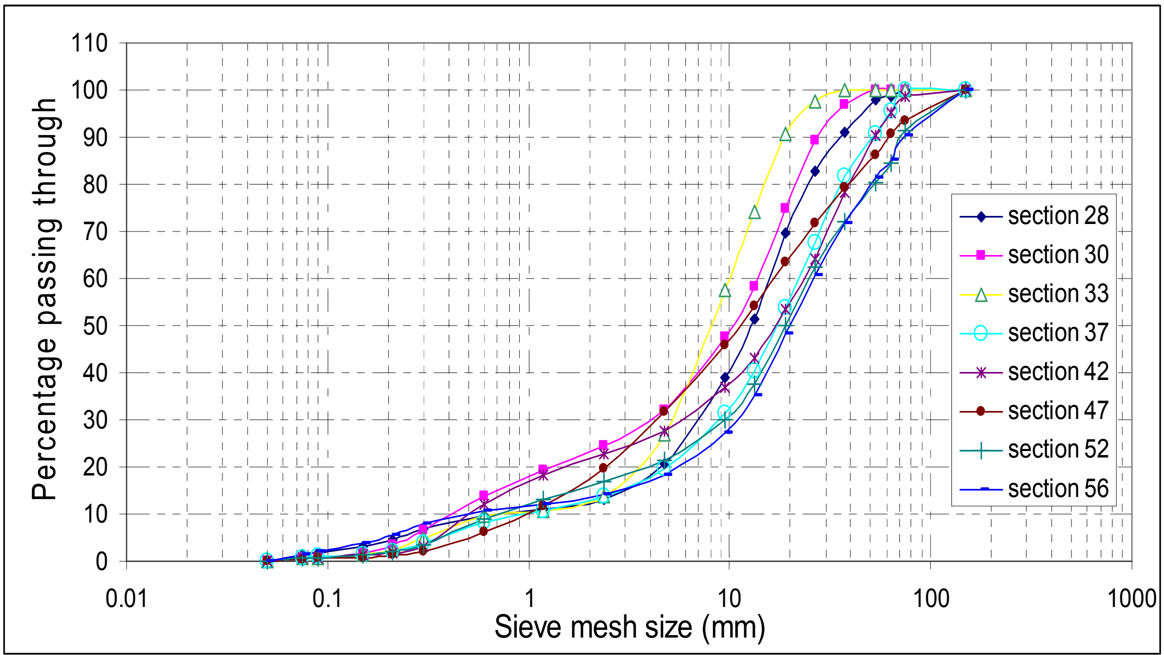

Figure 7 Whakatane River Gravel Bed Material – Whole of Bed

Table 1 Whirinaki River – Gravel Bed Material

	ARMOURING LAYER (mm)			WHOLE OF BED (mm)			
Cross section	d_{25}	d_{50}	d_{75}	d_{25}	d_{50}	d_{75}	d_{90}
1	6.00	26.50	51.10	7.80	25.00	53.40	66.70
2	13.20	36.17	56.60	10.70	30.20	53.00	87.50
3	22.78	51.30	75.20	4.25	16.57	38.30	66.70
4				11.00	17.80	30.00	41.30
5	17.50	53.10	90.00	2.87	19.30	53.00	100.00
6	7.10	37.60	74.80	5.50	30.30	66.67	127.85
7	3.00	60.00	143.16	2.00	19.30	69.67	142.85

Table 2 Whakatane River – Gravel Bed Material

WHOLE OF BED (mm)			
Cross section	d_{50}	d_{75}	d_{90}
28	13.00	22.20	35.80
29	17.00	37.50	56.30
30	10.20	19.00	26.50
31	6.00	10.00	17.11
32	13.20	30.00	46.70
33	8.00	13.20	19.00
34	13.20	35.00	53.00
35	10.00	21.00	31.70
36	17.60	33.00	53.00
37	18.00	31.70	53.00
38	12.10	23.00	35.00
39	11.40	20.00	34.00
40	14.80	30.00	63.00
41	16.80	25.00	37.50

42	17.60	35.00	53.00
43	21.00	44.00	63.00
44	9.00	19.00	28.00
45	11.40	30.00	63.00
46	24.50	48.00	67.00
47	22.30	53.80	75.00
48	8.40	18.30	30.00
49	20.00	43.00	63.00
50	20.00	40.00	60.00
51	17.00	32.00	53.00
52	20.00	43.00	73.00
53	11.40	24.00	42.00
54	10.00	19.00	32.00
55	22.00	50.00	63.00
56	20.00	42.50	75.00
57	17.00	32.50	63.00
58	10.00	18.00	25.00

4.3 Channel Design

4.3.1 Meander or Channel Widths

The purpose of this section is to provide some insight into the relationship between gravel transport rates and channel width, for given water discharge conditions at the upstream end of the study reach of the two rivers. Here, it is intended to address one type of problem important to both rivers.

- Redesigning the width of existing channels, where extensive bank erosion and/or aggradation have been observed, to a new “design width” at which it is believed the channel can be maintained in a dynamic equilibrium. The term dynamic equilibrium is used to denote a condition in which the bed, although in motion during flood events, is stable in the medium and long-terms because the rate of outflow of gravel from the reach equals the rate of supply. This is the so-called “regime” or “live-bed” condition.

In natural rivers water discharge is generally highly variable over time. Therefore, to apply stable channel theories to river control works (as described above), attempts have been made by various researchers to model the effects of a variable river discharge by a single representative flow rate. This single representative flow rate is known as the dominant discharge, Q_d, and is generally accepted as being the bank-full flow. In terms of recurrence intervals this corresponds in some rivers to the design mean annual flood or the design 2.33-year return period flood flow ($Q_{2.33}$).

Using the assumption that discharge Q is proportional to the catchment area to the power of 0.75 (Ref. TM61 with Q = 0.0139CRSA$^{3/4}$) and the relative catchment area, the design dominant discharge for the Whakatane River upstream of the Waimana confluence was taken as 642m^3/s. Q_2 downstream of the Waimana confluence was taken as 880 m^3/s (Blackwood, 1999) and that in the Whirinaki River at the Whirinaki Bridge is estimated at 154m^3/s. However, through modelling of the Whirinaki River, it is found that the bank full flow is only 99.60 m^3/s.

A variety of empirical formulae have been developed to assess the natural form of rivers under regime conditions. These formulae have, however, been derived from measurements on different types of rivers and they do not give consistent results. Where the derivation has been guided by theoretical considerations different approaches have also been used, although in general the aim has been to define a channel that is hydraulically efficient in transporting the available loose material of the channel. Thus the width and depth of the channel and the amount of sediment transported have been related to measurable parameters of flow, sediment size and channel slope.

The formulae do not define the plan configuration of the river channel. The width of the channel can be related to the radius of curvature of the meandering channel and to the meander wavelength, but the proportion of one to the other depends on the type of channel. A river channel can be wide and shallow with different sized channels forming within the actively worked area of loose bed material. It can also be narrow and deep with well-formed banks and bed, which maintain their general shape as material is moved down the channel. The channel type is probably related to the relative erodibility and transportability of bank material compared to bed material, and to the balance between available energy from the flow and the expenditure of energy on the transport of sediment derived from either catchment erosion or channel reworking.

In applying the regime formulae the type of channel that is being defined must be assumed. As consequence, in this study, specific formulae have been selected, to cover the range of channel types available in the Bay of Plenty. These formulae use different combinations of the main channel forming characteristics of flow, slope and material size and have been assumed to define different types of channels as described below and as shown in Table 3.

The Lacey formula was developed for flow regime under live bed conditions and has been in common use for many years in New Zealand. This formula was derived primarily from silt-carrying (sediment grain size ranging from 0.002mm to 0.06mm) rivers of low width-depth ratio in channels cut in cohesive sediment and with down channel slopes ranging from 0.0001 to 0.0003 (Carson and Griffiths, 1987).

- Lacey formula (Carson and Griffiths, 1987, page 89)

$$W = 4.85Q^{0.5} \tag{4.1}$$

Also under flow regime and live bed conditions, two formulae were developed in the USSR for stable channel design of steep gravel carrying rivers. These Russian formulae (Titchmarsh, 1992) are also in common use and are formulated as follows:

1 $$\mathbf{W} = \frac{1.45Q^{0.5}}{s^{0.2}} \tag{4.2}$$

2 $$\mathbf{W} = \frac{4.15}{s^{0.2}}\left(\frac{Q}{g^{0.5}}\right)^{0.4} \tag{4.3}$$

Where

- W = meander width (m)
- Q = dominant discharge (m^3/s)
- s = energy slope
- g = acceleration of gravity (m/s^2)

From consideration of incipient movement and hydraulic efficiency, bed material regime equations under the threshold of motion conditions have also been developed. The purpose of the design under the threshold of motion is to ensure that the adequate channel width is derived so that gravel in the channel does not become mobilised. In other words the channel bed material is on the verge of movement but stable. This is known as the fixed-bed condition. Formulae for slope and meander width under the threshold of motion conditions are as follows:

- Regime width at the critical slope for active bed (Carson and Griffiths, 1987 pages 82-83).

Critical slope $$s = \frac{0.335\,d^{1.15}}{Q^{0.46}} \quad (4.4)$$

And meander width $$W = \frac{1.22\,Q^{0.46}}{d^{0.15}} \quad (4.5)$$

- For channels with slopes greater than the critical slope (i.e., at actual slope)

1 Chang

$$W = \left(3.10 + 0.405\left(\ln\frac{0.672\,d^{1.15}}{s\,Q^{0.42}}\right)^2\right)Q^{0.47} \quad (4.6)$$

2 Henderson formula

$$W = \frac{2.065\,Q\,s^{1.167}}{d^{1.5}} \quad (4.7)$$

Where

- d is the effective size of bed material – d_{50} (m) and
- s is the slope of the channel.

The channel slope was taken as that of the river thalweg. The d_{75} of the whole of the bed was taken as the median size of the armouring layer material to represent the effective material size in the fixed bed (threshold of motion) regime formulae for the Whakatane River width estimation. The medium size of the armouring layer material was been taken as the effective material size of the fixed bed (threshold of motion) regime formulae for the Whirinaki River width values estimation.

Table 3 Channel Widths – Empirical Formulae

Formula		Parameters used to determine channel width			Channel type
		Flow	Slope	Material d_{50}	
Lacey		X			Relatively uniform single entrenched channel. Mobile bed of sand material. Flow dominant in channel formation. Sufficient energy to transport sediment load.
Russian		X	X		Relatively uniform channel, but wider and including gravel carrying rivers. Flow dominant in channel formation and sufficient energy to transport sediment load.
Threshold of Motion	Regime	X		X	Shallow channels within wide gravel carrying river channels. Channel formation associated with bed material movement, with the channel fixed on flood recessions and the threshold of motion. Sediment movement depends on the bringing into movement of the bed material.
	Chang	X	X	X	
	Henderson	X	X	X	

The width of the natural Whakatane River Middle Reach channel given by the selected formulae was part of a previous study (ref. Whakatane River Scheme – Middle Reaches Investigation by Titchmarsh, 1992) and is recorded in Table 4A.

The width of the natural channel given by the selected formulae is given in Table 4B when the parameter values determined for the Lower Whirinaki River (see Table 4B, columns 2 to 4) are used.

For most of the main channel length of the Whakatane River middle reach, the natural channel widths for the different types of meandering channels that can form are around the following:

Fixed bed (threshold of motion)

(1) Minor meander channel width at regime (critical) slope W_r – 38m
(2) Major meander channel width at actual slope W_s – 100m to 350m

Live bed (flow dominant)

(1) Lacey formula channel width W_L – 125m
(2) Slope adjusted (Russian formula) channel width W_R – 120m to 170m

For most of the main channel length of the Lower Whirinaki River, the natural channel widths for the different types of meandering channels that can form are around the following:

Fixed bed (threshold of motion)

(1) Minor meander channel width at regime (critical) slope W_r – 16m
(2) Major meander channel width at actual slope W_s – 24m to 60m

Live bed (flow dominant) –

(1) Lacey formula channel width W_L – 48m
(2) Slope adjusted (Russian formula) channel width W_R – 40m to 55m

The variation of the parameter values (i.e., Q_2, d_{50} and channel slope) along the main channel of Whakatane River Middle Reach and the Whirinaki River Lower Reach are not sufficient to greatly alter the natural channel widths, giving a similar form to the low flow channels along the main channel reach of both rivers.

The bed material sampling on both rivers is obviously of limited extent compared to the channel area. However the resulting grading curve (medium diameter sizes of armouring layer) of the Whirinaki River vary in a reasonably consistent manner, and most likely reflect actual variation in the bed material. The armouring layer, which is significantly affected by local condition of flow and slope, declines in size in a progressive manner down the main channel length of the lower Whirinaki River. Although there is some variability in bed material size that can be attributed to the change in channel slope and dominant flow, there is little change in these determining factors along the main channel of the river, and thus the change in size of the armouring material can be attributed primarily to a progressive decline in the whole of the bed material of the channel in the downstream direction. The little variability in the armouring bed material size combined with the little variability in channel slope give rise to homogeneous fixed bed channel widths in the Whirinaki River.

The Whakatane River experiences no progressive decline in the whole of the riverbed material. The change in size occurs randomly and is more apparent where a major change in slope occurs in the river. The combined change in bed material size and channel slope in the Whakatane River gives rise to substantially different fixed bed channel widths.

Table 4A Whakatane River Channel Widths

Whakatane River – Channel Widths (m)															
Reach (X/S)	Flow Q_2 (m^3/s)	Material d_{50} (mm)		Actual Slope	Critical Slope	Threshold Of Motion Widths (m)			Live Bed Regime Widths (m)			Measured Widths (m)		Design Fairway Widths (m)	
		Measured	Designed			At Critical Slope	At Actual Slope		Lacey	Russian		Minor	Major	Narr ow	Wide
						Regime	Henderson	Chang		(1)	(2)				
28	854	22	23	0.0008	0.0002	44	123	76	142	176	163	50	100	140	235
29	854	38	24	0.0010	0.0002	44	150	78	142	169	156	-	85	140	235
30	854	20	25	0.0009	0.0002	43	124	76	142	172	159	35	70	140	235
31	642	11	25	0.0008	0.0002	39	82	65	123	153	145	-	100	125	210
32	642	30	26	0.0005	0.0003	38	44	65	123	168	160	60	140	125	210
33	642	15	26	0.0007	0.0003	38	66	65	123	157	149	-	85	125	210
34	642	35	27	0.0031	0.0003	38	353	83	123	117	111	35	60	125	210
35	642	22	27	0.0021	0.0003	38	224	75	123	126	120	35	65	125	210
36	642	34	28	0.0011	0.0003	38	100	66	123	144	136	55	55	125	210
37	642	32	28	0.0011	0.0003	38	100	66	123	144	136	35	75	125	210
38	642	23	28	0.0015	0.0003	38	143	69	123	135	128	25	55	125	210
39	642	20	29	0.0011	0.0003	38	95	66	123	144	136	40	40	125	210
40	642	30	30	0.0023	0.0003	38	213	74	123	124	118	30	70	125	210
41	642	26	30	0.0025	0.0003	38	235	76	123	122	116	25	60	125	210
42	642	35	30	0.0007	0.0003	38	53	65	123	157	149	35	80	125	210
43	642	45	31	0.0013	0.0003	37	104	67	123	139	132	30	70	125	210
44	642	18	32	0.0014	0.0003	37	108	67	123	137	130	20	80	125	210
45	642	30	32	0.0022	0.0003	37	183	72	123	125	119	40	80	125	210
46	642	46	33	0.0020	0.0004	37	157	70	123	127	121	50	50	125	210
47	642	53	33	0.0010	0.0004	37	70	65	123	146	139	35	95	125	210
48	642	18	34	0.0027	0.0004	37	213	75	123	120	114	55	100	125	210
49	642	42	34	0.0029	0.0004	37	231	76	123	118	112	-	130	125	210
50	642	40	35	0.0015	0.0004	37	103	67	123	135	128	35	140	125	210
51	642	31	35	0.0026	0.0004	37	195	73	123	121	115	25	80	125	210
52	642	42	36	0.0023	0.0004	36	162	71	123	124	118	30	80	125	210
53	642	23	36	0.0017	0.0004	36	114	67	123	132	125	30	85	125	210
54	642	19	37	0.0020	0.0004	36	132	69	123	127	121	25	110	125	210
55	642	48	37	0.0020	0.0004	36	132	69	123	127	121	30	140	125	210
56	642	42	38	0.0020	0.0004	36	127	68	123	127	121	35	70	125	210
57	642	32	38	0.0022	0.0004	36	142	70	123	125	119	35	65	125	210
58	642	17	39	0.0022	0.0004	36	136	69	123	125	119	30	50	125	210

Table 4B Lower Whirinaki River Channel Widths

Lower Whirinaki River – Channel Widths (m)																
Reach (X/S)	Flow Q_2 (m^3/s)	Material d_{50} (mm)	Actual Slope	Critical Slope	Threshold Of Motion Widths (m)			Live Bed Regime Widths (m)			Measured Widths (m)		Design Low Flow Channel Widths (m)	Design Fairway Widths (m)	
					At Critical Slope	At Actual Slope		Lacey	Russian		Minor	Major			
					Regime	Henderson	Chang		(1)	(2)				Narrow	Wide
1	99.60	0.0265	0.0034	0.0002	16	63	29	48.4	45.1	51.6	25	80	30	50	84
2	99.60	0.0362	0.0025	0.0002	16	27	27	48.4	48.0	54.9	25	65	27	55	92
3	99.60	0.0513	0.0038	0.0002	16	27	27	48.4	44.1	50.5	35	55	27	50	84
4	99.60	0.0520	0.0043	0.0002	17	30	27	48.4	43.0	49.2	20	135	30	50	84
5	99.60	0.0531	0.0037	0.0003	16	24	27	48.4	44.3	50.7	20	45	27	50	84
6	99.60	0.0376	0.0026	0.0003	15	27	27	48.4	47.6	54.5	25	80	27	55	92
7	99.60	0.0600	0.0055	0.0003	15	32	27	48.4	41.0	46.9	45	105	30	50	84
8	99.60		0.0030	0.0003				48.4	46.2	52.9	25	50		50	84

4.3.2 Design Meander Patters

The threshold of motion meanders form on the recession of floods (or under low flow conditions) as sediment transport stops and the existing channels become fixed. The narrower (minor) meanders tend to be well formed with radius of around 4 times the width. The wider (major) meanders, which are influenced by the actual channel slope, tend to be more distorted with radius of around 6 times the width.

In steep gravel carrying rivers the flow dominant meanders of live bed conditions (see Russian formulae) do not form as a definite channel, but as flood phenomena that have an important influence on the size and shape of the overall active channel of the river. Well-defined entrenched channels of sand or silt carrying rivers do form according to flow dominant live bed conditions meander pattern (see Lacey formula), with the radius of curvature generally around 2 to 3 times the active channel width. The Middle Reach Whakatane and Lower Whirinaki Rivers are primarily gravel-carrying rivers. Both rivers are not very steep and the amount of silt carrying capacity is less than 20% of the average bed load. Careful attention and judgement should then be used on which value of the live bed flow dominant formulae values stored in Tables 4 should be used in deriving design meander widths.

The meander patterns of the low flow channel of the Whakatane and Whirinaki Rivers, as seen on the aerial photography (see Appendix A), follow the threshold of motion meander characteristics with differing combinations of the minor and major meanders. Although the different photography show relative channel position changes through meander migration over time, the same general meander pattern remains. This is more so in the Whakatane River despite the artificial control that has been exercised in the middle reach over the decade. The radius of the minor meander on the July 1998 aerial photography is around 3 to 4 times the design width of the narrow managed fairway and the wavelength is around 7 to 8 times the design width (Appendix A).

It is common practice in river engineering design works in New Zealand to use the Lacey or Russian formulae to design meander widths and radius of curvature for flow dominant live bed channel, with encrusted inside the dominant flow channel, a low flow channel derived through the threshold of motion meander formulae.

The concept described above is used to artificially control the Whakatane River where a design low flow channel width of 38m (see Table 4A) is used with a meander radius of about 3 to 4 times the channel width. The design low flow meandering channel is encrusted inside a design narrow fairway which width varies from 125m to 140m in the downstream direction. Those values were directly derived from the Lacey Formula. The meanders radius varies between 3 and 4 and their wavelength ranges between 7 and 9. Those values were selected so to fit the design meander pattern between the limits of the natural meander pattern of the river whilst endeavouring to utilise existing protection works and natural strong points. However, at points where no protection works exist it was suggested (Titchmarsh, 1992) to control potential migration trend of the river by continuous training works mostly at the outside of bends. That suggestion was adopted and the training works is reviewed from time to time. A wider design fairway of about 1.7 times the narrow design fairway was allowed for. Inside that wider design fairway, buffer zones of the same width as the low flow channel were suggested and adopted. The purpose of the wider fairway is to allow a downstream migration of the design narrow and low flow meanders.

The Lower Whirinaki River channels of the 1999 aerial photographs (Appendix A) and survey show a low flow channel width of around 20m to 35m (Table 4B) and a dominant flow width of between 50m to 130m (Table 4B). The small meander curvatures have a radius of around 60m to 100m (3 to 4 times low flow channel width). The major meander curvatures range between 180m to 300m (4 to 6 times dominant flow width).

The same concept used in the Whakatane River is proposed here for the Whirinaki River. However to avoid on-going lateral erosion and bed deepening, and shifting as in the Whakatane River (see section 4.3.3 below), the proposed design low flow channel widths are selected to represent the largest values derived from the threshold of motion meander formulae (Henderson and Chang) as well as to be able to fit into the natural low flow channel widths (see Table 4B) and meander pattern. Since the Whirinaki River is primarily a gravel-carrying river and there is need for avoidance of incessant erosion and erosion protection, a conservative approach is suggested, and the largest values derived from the Lacey and Russian formulae are suggested for the design narrow fairway width (see Table 4B). A design wide fairway two-thirds greater than the design narrow fairway is suggested. Continuous protection must also be provided around outside of bends and buffer zones of at least as wide as 30m are suggested on both sides of the channel and within the design wide fairway. It is recommend to set the meanders radius to about 2 to 3 times the design fairway widths, and the meanders wavelength to 6 to 11 times the design fairway widths, and that the design meander pattern follows as much as possible the natural river meander pattern.

4.3.3 Design Channels

The natural meander pattern of a river is generally used to guide the determination of design channel widths and shape. It can also guide the layout and spacing of river training works and the development of consistent vegetative buffer zone along the banks of the river. Three options of river channel design were assessed and described below and in Table 5.

4.3.3.1 *Narrow Managed Fairway Option*

The smaller (low flow or threshold of motion) meanders are highly mobile and must be allowed to migrate to avoid severe pressure on the channel banks. The channel must also have sufficient flood flow capacity to contain flood flows without generating excessive flood levels or velocities and be able to provide sufficient bed area for the transport of the imposed sediment load. The “live bed” flow dominant channel width allows sufficient channel area for the smaller meanders associated with bed material movement to form full meanders of adequate but not too great a curvature, and for migration of these meanders within the channel. At the same time the river channel remains relatively wide with small flood rises. This channel width and a radius of curvature of meander of around 4 times the width can be taken as the basis of a narrow managed fairway. The smaller (threshold of motion) meanders will form anywhere in the channel and by their formation can cause bank attack at any point and thus a requirement for bank protection. To satisfy this requirement of bank protection, a vegetative buffer zone (i.e., an erosion bay) with a minimum width equal to the width of the smaller of the mobile meanders should be considered. However, a more desirable width of the vegetative buffer zone is that of the larger of the mobile meander, or about twice that of the smaller mobile meander. This will allow more substantial erosion to occur whilst some of the vegetation remains in place after the bank erosion that takes place with a meander formation or migration has occurred. Also easily achievable is reestablishment of the buffer zone by lopping and layering as well as replanting. However, the choice of the preferred buffer zone width is obviously a matter of judgement.

The narrow managed fairway design channel option described above was used in training the middle reach of the Whakatane River. The vegetative buffer zone was selected as the smaller of the mobile meander widths. The design low flow channel widths adopted are the smaller value of the mobile meander widths (see section 4.3.1 above) resulting in over-confinement of the channel over some reaches of the channel, thus leading to increased cross-section asymmetry through lateral erosion, and deepening of the low flow channel against the riverbank over those reaches. Those failures (lateral and bed erosion) are prevalent at cross-sections 52, 51 50, 49, 48, 46, 45,42, 41, 40, and 38 to 34 (see Appendix B). The progressive occurrence of lateral erosion and deepening of the low flow channel bed will soon cause significant threat to the bank stability. Severe bank erosions through lateral erosion are prominent at cross-section 51, 49, 46, 42, 41, 40, and 36 (See Appendix B). Currently, selective gravel extraction and strengthening channel edge through layering of willow trees are the river maintenance methods used to try and keep bed equilibrium and bank stability. However, it appears that sooner or later, channel reshaping by dozing the channel bed will be required to limit low flow channel deepening. Dozing the channel bed has the ability to avoid the development of very entrenched river with very high banks. High and steep banks are hard to protect by vegetation. This is because under-scouring tends to take place at the bottom of high and steep banks below root zone of vegetation, thus leading to trees toppling into river channel becoming both a liability as well as an asset.

4.3.3.2 *Wider Managed Fairway Option*

Another river channel design option is the adoption of a wider fairway approach. A wider managed fairway width can be based on around 1.7 times the live bed flow dominant meander width. This allows room for the low flow meanders to form and migrate within the channel, but the channel is still not so wide that the low flow meanders will break up and divide. Thus the channel is kept to a semi-braided state rather than breaking-up into a fully braided condition. For wide shallow gravel rivers this point of transition is considered the best compromise between the conflicting requirements of minimised bank attack, low flood rise, efficient sediment transport and reduced channel area. This option is best suited to wide, shallow and extensively braided rivers where the braiding is to be restrained to a minimum.

4.3.3.3 *Extreme Minimum Managed Fairway Option*

The extreme minimum width would be that of the major meander associated with bed material movement. This meander form takes into account the actual slope of the river channel, and in this case a radius of curvature of around 6 times the channel width could be used when determining the design channel. In this approach the active channel forms are constrained and prevented from migrating, and consequently more severe bank erosion will occur as the channel attempts to move as part of the process of moving bed material through erosion deposition. This option is best applied to rivers with strong banks.

The three design channels described above imply different level of bank attack and erosion as well as affecting flood levels and sediment transport processes, and the required management policies differ accordingly. The wide fairway approach relies on vegetation to contain bank erosion. With the narrow fairway approach, the channel edge generally requires strengthening to prevent excessive bank erosion. With the extreme minimum fairway approach, strong channel banks are required to control severe pressure for channel movement through erosion and deposition.

The lower reach of the Whirinaki River has a relatively wide and shallow channel that tends to form a single low flow channel around the major meander pattern. The river moved medium to large sized gravel material, and from visual observation of the aerial photographs of the studied reaches it appears that the migration of the meanders is relatively slow. Observation also shows that large erosion bays can be formed in those reaches during a single flood event. Furthermore, the channel banks are not in themselves strong enough to provide erosion protection against severe pressure from channel movement. It can therefore be argued that both the extreme minimum width fairway and the wider managed fairway are not adequate design measures for the lower reach of the Whirinaki River. The minimum fairway option will require constant and expensive protective works of the riverbanks, whilst the wider fairway option may require acquisition of land adjacent to the river and probably the nature of the river will change from a basically single channel river to semi-braided river.

The adjacent landowners may not also be willing to part with their land. The narrow managed fairway seems on the other hand more appropriate and is recommended as described in section 4.3.2. The recommended widths of the fairway are as in Table 4B. The minimum vegetative buffer zone width suggested is that of at least the minor threshold of motion meander widths. An average value of 30m is recommended for the Whirinaki River.

Table 5 Design Channels – Narrow Managed Fairway Option

River	Widths for the main channel reach (in m)		
	Channel	**Buffer Zone**	**Total**
Middle Reach Whakatane River	125 to 140	38	201 to 216
Lower Reach Whirinaki River	50	30	110

Chapter 5: Channel Resistance

5.1 General

The resistance to flow of a channel depends on the characteristics of the channel, its width and thus depth of flow, the size of the exposed bed material, the changing form of the channel and the presence of vegetation and obstructions. In determining the transport of bed material the proportion of the flow energy that is spent on moving the bed material must be estimated. This proportion of energy dissipated in moving the bed material is simply taken to be proportional to the grain roughness part of the channel resistance. The remaining energy is then dissipated in the turbulence generated by changes in the channel form.

5.2 Theoretical Relationships

The grain roughness proportion of the channel resistance can be estimated through the use of semi theoretical relationships. A number of different approaches have been developed, where empirical relationships have been generated in terms of parameters involving bed material size, the depth and gradient of flow, and the Reynolds or Froude number.

Simple relationships between channel resistance and bed material size, or the relative depth of the bed material (flow depth divided by bed material size) have been developed. The following two formulae are examples of that relationship. The formulae are simple relationship between the Manning's n resistance factor and the bed material size d.

$$n = 0.038d^{0.167} \quad (5.1)$$

Where d = d_{75} of the armouring layer or d_{90} or $2d_{65}$ of the whole of the bed material (in m)

$$n = 0.041d^{0.167} \quad (5.2)$$

Where d = d_{50} of the armouring layer or d_{75} of the whole of the bed (in m)

Also possible is the derivation of resistance to flow through the use of slope s of the channel bed. Such relationship is derived from Lacey regime theory and is given is as follows:

$$n = 0.104\, s^{0.178} \quad (5.3)$$

5.3 Derived Resistance

The overall resistance of the middle reach channels of the Whakatane River was determined through the calibration of the hydraulic model of the river based on the July 1998 flood event. The calibration was undertaken using the HECRAS computer programme. Flood level data were collected in forms of silt and debris lines. The flood flows used in calibrating the model were derived through deduction of flood levels recorded at Valley Road gauging station and at Waimana Gorge station. The calibrated resistance to flow values are in Table 6. The calibrated floodwater levels were used in place of the bed gradient to derive the bed resistance to flow with the Lacey equation above.

The overall resistance of the lower reach of the Whirinaki River channels can be determined using either the HECRAS computer programme or visual estimation or computation (Equations 5.1, 5.2, 5.3) based on the river characteristics, the riverbed slope, the riverbed material size and the river channel vegetation. Good and reliable flood flow and flood level data are almost non-existent on the Whirinaki River, and it is thus suggested to use only visual observation and the theoretical relationships (Equations 5.1, 5.2, 5.3) based on the gradient of the mean bed levels and the gravel grain size (whole of the bed material size) to derive the bed resistance. The results of the computation and visual observation are in Table 6 and Figure 9.

Table 6 Whakatane River – Channel Resistance

Cross sections	Whole of the bed material size (mm)		Slope s (m/m)	Channel resistance			
	d_{75}	d_{90}		Strickler criterion		Slope criterion	Calibrated
				d_{75}	d_{90}		
28	22.2	35.8	0.00054	0.022	0.022	0.0273	0.025
29	37.5	56.3	0.00096	0.024	0.024	0.0302	0.025
30	19	26.5	0.00072	0.021	0.021	0.0287	0.025
31	10	17.11	0.00024	0.019	0.019	0.0236	0.025
32	30	46.7	0.00031	0.023	0.023	0.0247	0.025
33	13.2	19	0.00042	0.020	0.020	0.0261	0.030
34	35	53	0.00248	0.023	0.023	0.0357	0.035
35	21	31.7	0.00112	0.022	0.021	0.0310	0.025
36	33	53	0.00118	0.023	0.023	0.0313	0.025
37	31.7	53	0.00314	0.023	0.023	0.0373	0.025
38	23	35	0.0021	0.022	0.022	0.0347	0.025
39	20	34	0.00044	0.021	0.022	0.0263	0.025
40	30	63	0.00345	0.023	0.024	0.0379	0.030
41	25	37.5	0.00087	0.022	0.022	0.0297	0.025
42	35	53	0.00248	0.023	0.023	0.0357	0.025
43	44	63	0.00183	0.024	0.024	0.0339	0.035
44	19	28	0.00154	0.021	0.021	0.0328	0.025
45	30	63	0.00145	0.023	0.024	0.0325	0.030
46	48	67	0.00369	0.025	0.024	0.0384	0.040
47	53.8	75	0.00064	0.025	0.025	0.0281	0.030
48	18.3	30	0.00079	0.021	0.021	0.0292	0.030
49	43	63	0.00171	0.024	0.024	0.0335	0.030
50	40	60	0.00249	0.024	0.024	0.0358	0.030
51	32	53	0.00317	0.023	0.023	0.0373	0.030
52	43	73	0.00208	0.024	0.025	0.0346	0.030
53	24	42	0.00261	0.022	0.022	0.0361	0.040
54	19	32	0.00191	0.021	0.021	0.0338	0.040
55	50	63	0.0026	0.025	0.024	0.0361	0.040
56	42.5	75	0.00232	0.024	0.025	0.0351	0.040
57	32.5	63	0.00338	0.023	0.024	0.0381	0.040
58	18	25	0.00151	0.021	0.021	0.0320	0.040

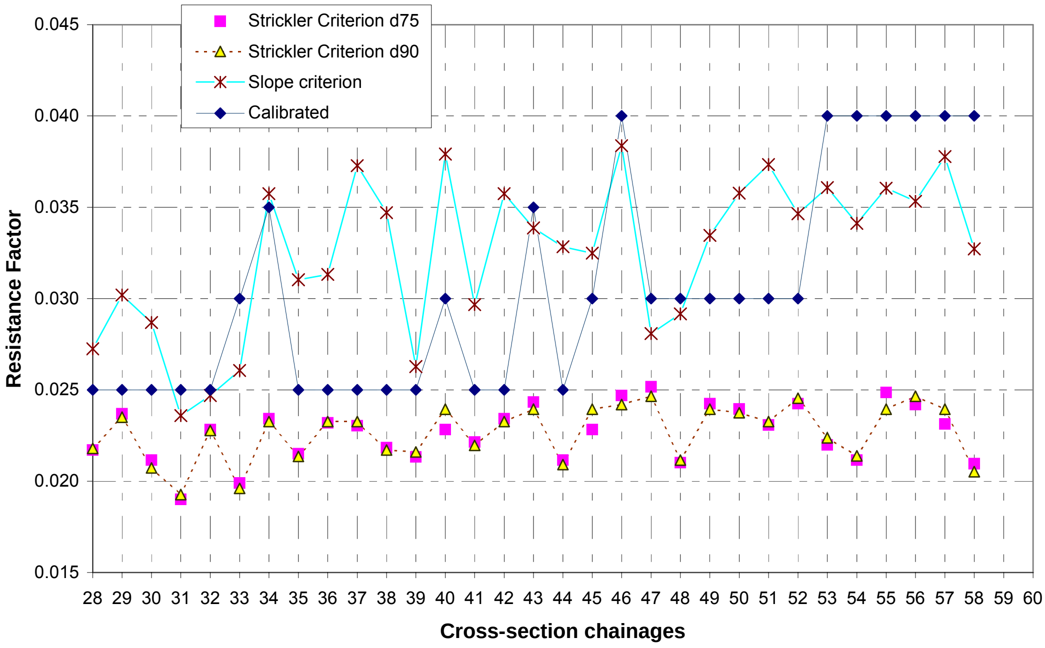

Figure 8 Whakatane River – Channel Resistance

Table 7 Whirinaki River – Channel Resistance

Cross section	Armouring layer (mm)		Slope s (m/m)	Channel resistance			
	d_{75}	d_{50}		Derived through Observation	Strickler criterion d_{75}	Strickler criterion d_{90}	Slope criterion
1	0.0511	0.0265	0.0034	0.035	0.0231	0.0224	0.0378
2	0.0566	0.0362	0.0025	0.031	0.0235	0.0236	0.0358
3	0.0752	0.0513	0.0038	0.035	0.0247	0.0250	0.0386
4	0.0413	0.0300	0.0043	0.040	0.0223	0.0228	0.0394
5	0.0900	0.0531	0.0037	0.035	0.0254	0.0251	0.0384
6	0.0748	0.0376	0.0026	0.037	0.0246	0.0237	0.0360
7	0.1432	0.0600	0.0055	0.044	0.0275	0.0256	0.0412
8			0.0030	0.037			0.0370

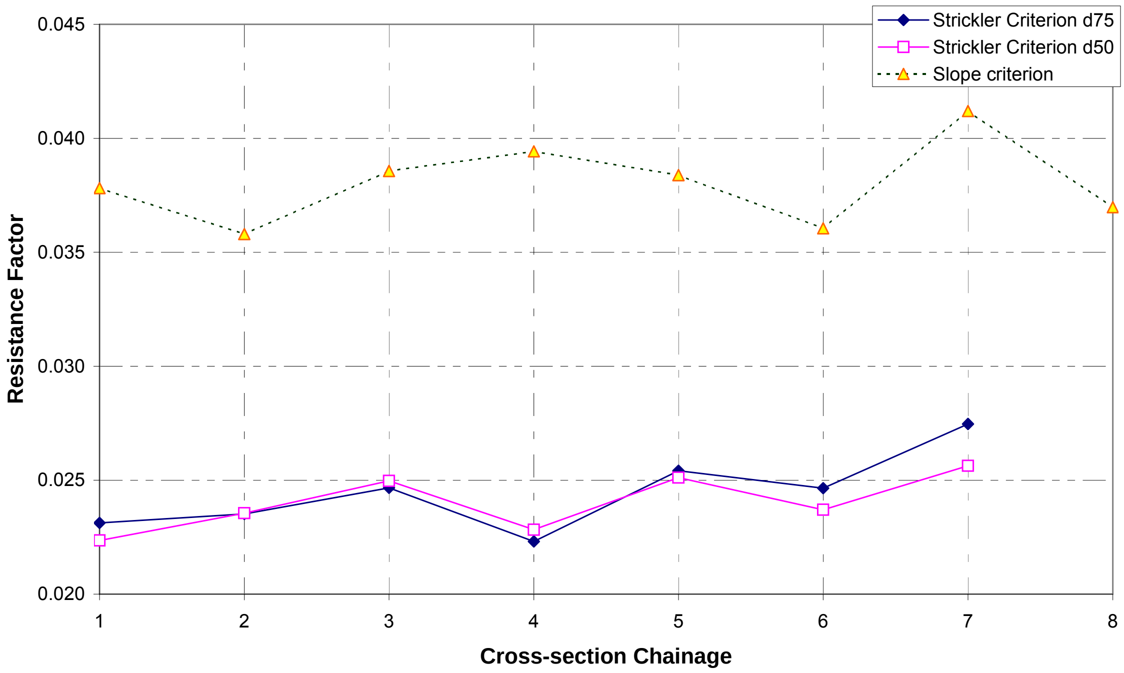

Figure 9 Whirinaki River – Channel Resistance

5.4 Channel Resistance Comparisons

The slope and bed material criteria for channel resistance described in section 5.2 have been applied at selected cross sections along the middle reach of the Whakatane River and lower reach and Whirinaki River. The results of the calculations are in Tables 5 and 6 and Figures 8 and 9. For the Whakatane River the d_{75} and d_{90} of the whole of the bed material are used to represent the d_{50} and d_{75} of the armouring layer respectively. This is because the only available grain size data for the Whakatane River are those of the measured whole of bed material. For the Whirinaki River the d_{75} and d_{90} of the whole of the bed material are used to represent the d_{50} and d_{75} of the armouring layer respectively at cross-section 4.

The results in Table 5 and Figure 8 show that on most of the Whakatane River middle reach (cross-section 52 to 28) the slope criterion resistance values are larger than the calibrated values. The only exceptions are the values upstream of cross section 53. The two forms of the Strickler criterion give lower values than both the slope criterion and calibrated resistance values but are similar to each other. This Strickler criterion generally underestimates channel resistance in steep gravel rivers. Although the slope criterion resistance factors are over-estimations they are relatively close to the calibrated resistance factors. Another interesting fact is that the derived slope criterion resistance factors tend to somewhat follow the same pattern as the bed material (Strickler) criterion factor, but not in a strictly correlated manner. This trend is observed for the Whirinaki River values.

From Figure 8 it is apparent that the calibrated resistance factors upstream of the river bend at Ohutu Bridge (cross-section 45) are greater than those downstream. Even at places downstream of cross-section 45 where the channel grade suddenly increased this trend persists. From this it can be inferred that most, if not all, of the channel resistance arises from grain roughness, with the energy of the river flows being dissipated almost entirely on sediment transport. This is also assumed true for the

Whirinaki River. This finding is valuable since when estimating the transport of bed material in a channel, the available energy is proportioned according to the ratio of the grain roughness to the total roughness of the channel. The total roughness here is be taken as:

- The calibrated resistance factor for Whakatane River, and
- The calibrated resistance factor derived through river form roughness (i.e., due to variation in channel geometry due to bed forms and including the effects of vegetation and any obstruction in the channel) for Whirinaki River.

Chapter 6: Channel Geometry

6.1 Channel Survey

Cross section lines for repeat surveys have been laid out along the Whakatane and Whirinaki Rivers and surveys have been undertaken since 1963 and 1994 for both rivers respectively.

The first series of surveys were carried out on the Whakatane River between 1963 and 1970. These surveys were undertaken at the time of the major channel works from upstream of the Ruatoki Valley to the mouth of the river. The second series of surveys followed in 1977. Upstream of the Pekatahi Bridge repeat surveys were carried out in 1991, 1994, 1996, 1998 and 1999, whereas downstream of the bridge the surveys were undertaken in 1984, 1992, 1993, 1996, 1998, and 1999. There are 35 cross section lines below the Pekatahi Bridge and 34 lines above the Pekatahi Bridge. The cross section lines spacing ranges between 300m to 750m below the Pekatahi Bridge, and from 500m to 1200m above the bridge. In a recent study entitled "Natural Environment Regional Monitoring Network River and Stream Channel – Monitoring Programme 1998/99" (Surman, 1999) it was suggested that the frequency of survey be set to 2 to 5 year and 1 year below and above the Pekatahi Bridge respectively. This is to help understand the changes in the river channel (aggradation and degradation) and to monitor gravel extraction and maintain river capacity. The suggested 1-year frequency of survey above the Pekatahi Bridge is part of the monitoring of gravel extraction activity, which became a very important river management practice.

Only three sets of surveys were carried out on the lower reach of the Whirinaki River using common cross section lines. The first survey was carried out in November 1994, followed by that in November 1997 and July 1999. The spacing between the cross section lines ranges from 550m to 1400m.

6.2 Channel Changes

A report by Surman (titled "Natural Environment Regional Monitoring Network River and Stream Channel – Monitoring Programme 1998/99", 1999) dealt with riverbed changes in the Whakatane and Whirinaki Rivers. Changes in cross section areas and volume of bed material are tabled in Appendix II and in Chapter 3 of that report.

6.3 Width/Depth Ratio

The width to depth ratio of a well-formed river channel varies with the depth of flow. In a well-formed channel the minimum value of the width to depth ratio is obtained when the top of the banks of the main channel (i.e., bank-full level) has been reached. The magnitude of this minimum value depends on the general shape of the channel, with wide shallow channels having large values and narrow deeply entrenched channel having low values. The magnitude of the minimum width/depth ratio then provides an indication of channel shape, and changes in channel can be simply represented through the use of this ratio.

Table 8 Whakatane River – November/December 1998 surveyed cross section minimum width/depth ratios

Cross section No.	Discharge (m^3/s)	Water Depth Main Channel (at Bank Full)	Water Depth Wider Channel (at Bank Full)	Main Channel Width	Wider Channel Width	Main Channel Width/Depth	Wider Channel Width/Depth
28	880	6.00		100		17	
29	880	5.00		140		28	
30	642	6.50		140		22	
31	642	5.20		160		31	
32	642	3.80		160		42	
33	642	4.00		160		40	
34	642	3.70		100		27	
35	642	3.70		100		27	
36	642	4.60		120		26	
37	642	3.10		115		37	
38	642	5.30		95		18	
39	642	5.60		140		25	
40	642	4.00		85		21	
41	642	3.30		150		45	
42	642	3.45		175		51	
43	642	4.10	1.85	106	956	26	517
44	642	4.10		155		38	
45	642	2.30		180		78	
46	642	3.00		120		40	
47	642	5.40		184		34	
48	642	3.85		170		44	
49	642	2.60		200		77	
50	642	3.40		180		53	
51	642	3.00		170		57	
52	642	3.66		135		37	
53	642	3.40		198		58	
54	642	3.90		268		69	
55	642	3.85	1.55	150	750	39	484
56	642	2.43		165		68	
57	642	4.60		120		26	
58	642	2.60		359		138	

Table 9 Whirinaki River – July 1999 surveyed cross section minimum width/depth ratios

Cross section No.	Discharge (m^3/s)	Water Depth Main Channel (at Bank Full)	Water Depth Wider Channel (at Bank Full)	Main Channel Width	Wider Channel Width	Main Channel Width/Depth	Wider Channel Width/Depth
1	99.60	3.28	1.4	32	107	10	76
2	99.60	2.60		84	-	32	-
3	99.60	2.20		70	-	32	-
4	99.60	1.80	0.74	25	135	14	182
5	99.60	3.90		85	-	22	-
6	99.60	2.60		105	-	40	-
7	99.60	1.60		105	-	66	-
8	99.60	4.00		40	-	10	-

In this study the width/depth ratios have been calculated only for the 1998/1999 cross sections of the Whakatane River above the Pekatahi Bridge and the lower Whirinaki River (see Tables 8 and 9 above). The results provide some comparative information, and show the variability of the river channel. Both studied river reaches are relatively wide and shallow as is reflected by the high ratio values.

Over some river reaches, a wider channel incorporating a main defined channel can be observed. This main defined channel is related to low flows, and sometimes can be very narrow. The ratio values for both the wider channel as a whole and the internal (main) channel where it exists are given in the Tables 8 and 9.

The Whakatane River upstream of the Ohotu Bridge is wider and shallower as compared to downstream of the bridge. This could explain why the calibrated resistance factors and those derived through empirical relationships are greater upstream of the Ohutu Bridge as compared to downstream of the bridge. The fact that both rivers show the characteristics of wide, shallow (Tables 8 and 9) and mostly semi braided to meandering river channels validate the adequacy of the decision to use the design narrow managed fairway for the Whakatane River and consolidate the proposal to use the design narrow managed fairway for the Whirinaki River.

The results of the Whirinaki River in Table 8 show that at around cross section 7 (between cross sections 7 and 6) the main channel is wider and shallower. This suggests that the channel around that sub-reach will have the tendency to braid during high flow. It is therefore possible to consider a wider managed fairway through that sub-reach of the river, because a narrow managed fairway over those sub-reaches might require substantial bank protection work.

Chapter 7: Bed Material Transport

This study attempts to look objectively at the sediment transport theories available and to assess and point out as a guide to decision making the important points to be considered in dealing with gravel extraction and channel protection in the Whakatane and Whirinaki Rivers.

7.1 Empirical Transport Formulae

A variety of transport formulae have been developed from a mixture of theoretical, laboratory and field measurement. Generally they are formulated in terms of a transport parameter and a flow parameter, with a ripple factor, f, proportioning the amount of shear stress used in transport. Three formulae have been used to estimate bed material transport rates in this study. They are as follows:

- Meyer-Peter & Muller

$$t = 25\left(fDs - 0.079d \right)^{1.5} \quad (7.1A)$$

and $$f = \left(\frac{k}{k^*}\right)^{1.5} or \left(\frac{n^*}{n}\right)^{1.5} \quad (7.1B)$$

- Engelund & Hansen

$$t = 0.021 v^2 d^{0.5} \left(\frac{Ds}{1.65d}\right)^{1.5} \quad (7.2A)$$

where $$v = c^* (Ds)^{0.5} \quad (7.2B)$$

- Einstein & Brown

$$t = 50 \frac{(fDs)^3}{d^{1.5}} \quad (7.3)$$

where:

t = volumetric bed movement per unit width, including voids (m^2/s)

D = depth of flow (m)

d = effective stone diameter, taken as the d_{50} of the whole of the bed material (m)

s = energy slope

f = proportion factor with respect to the bed roughness

k = roughness factor of the channel

k* = roughness due to the bed material size

n = Manning's friction factor for the channel

n* = Manning's friction factor for the whole bed material size

v = effective velocity (m/s)

c* = modified Chezy friction factor, and $c^* = R^{1/6}/n$ (R=hydraulic radius)

The factor f proportions the available energy of flow according to its effectiveness in transporting bed material, and is determined from an estimated proportion of the total roughness generated by the bed material. The grain roughness part of the channel resistance generated by the bed material can be estimated from the size of the material (see Chapter 5). In this study it was assumed that nearly all the roughness arises from the grain roughness of the bed material.

7.2 Bed Transport Rates in the Whakatane River

Sediment transport rates were calculated at each river cross section, using flow levels, velocities, energy slopes and channel resistances at the sections, as given by the HEC-RAS hydraulic modelling of the river channel.

Representative flow depths, D, were used to calculate the unit transport rates at the sections, and this rate was then multiplied by the active width of the channel. Generally an average bed level across the main channel, where transport activity takes place, was used to determine the representative flow depths. This average bed level was determined in Hilltop and from cross-section plots, and is essentially the mean bed level of the channel, but excludes the bank itself and the higher part of the beach where there would be minimal transport activity. For some cross sections, where channel asymmetry or variations meant a single flow depth would not be representative, the active width was divided into two (or more) parts.

The grain resistance, n*, estimated from the size of the bed material was used as a guide in determining the active proportion of the channel resistance arising from the transport of bed material. However, in general the reach values of the channel resistance, n, determined through the hydraulic modelling were used, with a small and consistent reduction to account for the form resistance part, which would generally be the same along the river.

The grading curves from the bed material samples taken along the river channel (see Section 4.2) were used to determine an effective stone diameter, d_{50}. However, an average of the sample medium sizes was used, as the effective stone size should be representative of the bed material being transported along the reach.

The hydraulic modelling calculates energy slopes, s, at the model sections, but these slopes are derived from an iterated solution, and actual slopes along river reaches should be used. A profile plot of both bed and calculated water levels at the sections was used to determine where there were effective changes in slope, and reach gradients were then calculated from this data.

The hydraulic modelling assumes a fixed bed at each section and the resulting flow area and velocity values are not, therefore, always based on a realistic balancing of area (or flow depth) and velocity from section to section. Consequently the resulting transport rates must be averaged over a number of cross sections to give reach values.

Three empirical formulae were used to calculate the sediment transport rates, being the Meyer-Peter & Muller, Engelund & Hansen, and Einstein & Brown formulae. The results were calculated on a spreadsheet, and the input data and results for each section are given in Tables 10 to 15, and graphed on Figures 12 to 14, for flood flows of the estimated 2, 5, 10, 20, 50 and 100 year return period peak flow.

In the 'sediment transport' columns of Tables 10 to 15 the values in bold are considered 'outliers', which arise from the use of hydraulic modelling data and difficulties in obtaining representative depths at some cross sections. There are also some short reaches with over-steep and over-flat grades (because of localised obstructions and constrictions) which are unrepresentative of the overall transport capacity of the river. They do though indicate areas where localised sediment deposition and channel distortions can occur.

Sediment transport rates for the middle reaches of the Whakatane River are given in Table 16 and graphed on Figure 15. These values are based on an average of the calculated rates, excluding the outliers.

Table 10 Whakatane River – bed material transport – 2 year return period flood flow

Cross Section	Profile Distance (m)	Bed Material d50 (mm)	Energy Slope	Channel Width (m)	Mean Bed Level (m)	Flood Level (m)	Flood Depth (m)	Effective Velocity (m/s)	Resistance		Sediment Transport		
									Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	10.27	4.68	2.97	0.025	0.0225	**0.18**	**0.11**	**0.07**
29	21355	13.0	0.00075	70	6.60	10.80	4.20	2.65	0.025	0.0225	**0.12**	**0.07**	**0.05**
30	22515	13.0	0.00075	88	7.42	12.01	4.59	2.60	0.025	0.0225	**0.18**	**0.09**	**0.08**
31	23285	13.0	0.00055	119	9.43	12.55	3.12	1.79	0.025	0.0225	**0.03**	**0.02**	**0.01**
32	23515	13.0	0.00035	150	9.66	12.64	2.98	1.52	0.025	0.0225	**0.00**	**0.01**	**0.00**
33	24040	13.0	0.00035	115	10.22	12.83	2.61	1.17	0.03	0.0225	**0.00**	**0.00**	**0.00**
34	24530	13.0	0.00085	84	10.48	13.21	2.73	1.86	0.03	0.0225	**0.02**	**0.02**	**0.01**
35	25120	13.0	0.00130	79	10.88	14.22	3.34	3.04	0.025	0.0225	0.28	0.16	0.14
36	25601	13.0	0.00130	96	12.14	14.75	2.61	2.69	0.025	0.0225	0.19	0.10	0.08
37	26185	13.0	0.00220	71	12.49	15.21	2.72	3.57	0.025	0.0225	**0.46**	**0.32**	**0.32**
38	26610	13.0	0.00235	70	13.64	16.34	2.70	3.50	0.025	0.0225	**0.51**	**0.33**	**0.37**
39	27235	13.0	0.00100	123	15.11	17.33	2.22	1.94	0.025	0.0225	0.08	0.04	0.03
40	28025	13.0	0.00100	80	15.54	18.22	2.68	2.23	0.025	0.0225	0.09	0.04	0.03
41	28580	13.0	0.00175	132	16.94	19.18	2.24	2.79	0.025	0.0225	0.37	0.19	0.17
42	29550	17.0	0.00175	104	18.32	20.47	2.15	2.61	0.025	0.0225	0.21	0.09	0.08
43	30060	17.0	0.00175	92	19.24	22.19	2.95	2.88	0.025	0.0225	0.39	0.17	0.18
44	30785	17.0	0.00175	111	20.85	23.74	2.89	2.74	0.025	0.0225	0.45	0.17	0.20
45	31630	17.0	0.00175	99	22.21	23.69	1.48	1.73	0.03	0.0275	0.07	0.02	0.03
46	32170	17.0	0.00300	99	23.34	24.83	1.49	2.19	0.03	0.0275	0.33	0.08	0.14
47	32660	17.0	0.00250	127	24.62	27.36	2.74	3.13	0.03	0.0275	**1.01**	**0.41**	**0.62**
48	33405	17.0	0.00085	140	26.34	28.01	1.67	1.23	0.03	0.0275	**0.00**	**0.01**	**0.01**
49	33715	17.0	0.00155	158	27.33	28.49	1.16	1.37	0.03	0.0275	0.01	0.01	0.01
50	34440	17.0	0.00220	151	29.20	30.47	1.27	1.64	0.03	0.0275	0.14	0.03	0.05
51	34955	17.0	0.00220	131	29.55	31.58	2.03	2.05	0.03	0.0275	0.43	0.10	0.18
52	35695	17.0	0.00220	123	31.22	33.31	2.09	2.19	0.03	0.0275	0.43	0.11	0.18
53	36635	17.0	0.00220	140	32.90	35.21	2.31	1.79	0.04	0.0350	0.52	0.09	0.23
54	37275	17.0	0.00220	202	35.45	36.74	1.29	1.31	0.04	0.0350	0.15	0.03	0.06
55	38675	17.0	0.00220	85	37.55	39.70	2.15	1.65	0.04	0.0350	0.27	0.04	0.11
56	39475	17.0	0.00220	125	39.08	41.25	2.17	1.72	0.04	0.0350	0.41	0.07	0.17
57	40260	17.0	0.00220	104	40.38	43.21	2.83	1.96	0.04	0.0350	0.60	0.11	0.31
58	41660	17.0	0.00220	193	44.22	46.19	1.97	1.73	0.04	0.0350	0.50	0.10	0.19

Table 11 Whakatane River – bed material transport – 5 year return period flood flow

Cross section	Profile distance (m)	Bed material d50 (mm)	Energy slope	Channel width (m)	Mean Bed level (m)	Flood level (m)	Flood Depth (m)	Effective Velocity (m/s)	Resistance		Sediment transport		
									Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	10.62	5.03	3.10	0.025	0.0225	**0.21**	**0.14**	**0.09**
29	21355	13.0	0.00075	70	6.60	11.41	4.81	2.90	0.025	0.0225	**0.16**	**0.10**	**0.07**
30	22515	13.0	0.00075	88	7.42	12.61	5.19	2.70	0.025	0.0225	**0.24**	**0.12**	**0.11**
31	23285	13.0	0.00055	119	9.43	13.08	3.65	1.91	0.025	0.0225	**0.05**	**0.03**	**0.02**
32	23515	13.0	0.00035	150	9.66	13.14	3.48	1.59	0.025	0.0225	**0.00**	**0.01**	**0.01**
33	24040	13.0	0.00035	115	10.22	13.32	3.10	1.31	0.03	0.0225	**0.00**	**0.01**	**0.00**
34	24530	13.0	0.00085	84	10.48	13.59	3.11	1.98	0.03	0.0225	**0.04**	**0.03**	**0.01**
35	25120	13.0	0.00130	79	10.88	14.62	3.74	3.17	0.025	0.0225	0.35	0.21	0.19
36	25601	13.0	0.00130	96	12.14	15.14	3.00	2.82	0.025	0.0225	0.26	0.14	0.12
37	26185	13.0	0.00220	71	12.49	15.62	3.13	3.52	0.025	0.0225	**0.60**	**0.38**	**0.48**
38	26610	13.0	0.00235	70	13.64	16.69	3.05	3.69	0.025	0.0225	**0.63**	**0.44**	**0.54**
39	27235	13.0	0.00100	123	15.11	17.61	2.50	2.02	0.025	0.0225	0.11	0.05	0.04
40	28025	13.0	0.00100	80	15.54	18.40	2.86	2.19	0.025	0.0225	0.11	0.04	0.04
41	28580	13.0	0.00175	132	16.94	19.41	2.47	2.90	0.025	0.0225	0.45	0.24	0.22
42	29550	17.0	0.00175	104	18.32	20.66	2.34	2.75	0.025	0.0225	0.26	0.12	0.10
43	30060	17.0	0.00175	92	19.24	22.40	3.16	2.84	0.025	0.0225	0.45	0.18	0.22
44	30785	17.0	0.00175	111	20.85	23.87	3.02	2.83	0.025	0.0225	0.49	0.20	0.23
45	31630	17.0	0.00175	99	22.21	23.88	1.67	1.84	0.03	0.0275	0.11	0.03	0.04
46	32170	17.0	0.00300	99	23.34	24.98	1.64	2.35	0.03	0.0275	0.40	0.11	0.18
47	32660	17.0	0.00250	127	24.62	27.57	2.95	3.29	0.03	0.0275	**1.16**	**0.51**	**0.77**
48	33405	17.0	0.00085	140	26.34	28.20	1.86	1.32	0.03	0.0275	**0.00**	**0.01**	**0.01**
49	33715	17.0	0.00155	158	27.33	28.62	1.29	1.44	0.03	0.0275	0.03	0.02	0.02
50	34440	17.0	0.00220	151	29.20	30.61	1.41	1.74	0.03	0.0275	0.19	0.05	0.07
51	34955	17.0	0.00220	131	29.55	31.69	2.14	2.12	0.03	0.0275	0.48	0.11	0.21
52	35695	17.0	0.00220	123	31.22	33.44	2.22	2.22	0.03	0.0275	0.49	0.12	0.22
53	36635	17.0	0.00220	140	32.90	35.36	2.46	1.82	0.04	0.0350	0.60	0.11	0.27
54	37275	17.0	0.00220	202	35.45	36.89	1.44	1.40	0.04	0.0350	0.22	0.04	0.08
55	38675	17.0	0.00220	85	37.55	39.77	2.22	1.70	0.04	0.0350	0.29	0.05	0.12
56	39475	17.0	0.00220	125	39.08	41.36	2.28	1.79	0.04	0.0350	0.45	0.08	0.20
57	40260	17.0	0.00220	104	40.38	43.34	2.96	2.03	0.04	0.0350	0.66	0.13	0.36
58	41660	17.0	0.00220	193	44.22	46.34	2.12	1.83	0.04	0.0350	0.59	0.12	0.24

Table 12 Whakatane River – bed material transport – 10 year return period flood flow

Cross section	Profile distance (m)	Bed material d50 (mm)	Energy slope	Channel width (m)	Mean Bed level (m)	Flood level (m)	Flood Depth (m)	Effective Velocity (m/s)	Resistance		Sediment transport		
									Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	11.25	5.66	2.87	0.025	0.0225	**0.27**	**0.14**	**0.13**
29	21355	13.0	0.00075	70	6.60	11.50	4.90	2.94	0.025	0.0225	**0.17**	**0.10**	**0.07**
30	22515	13.0	0.00075	88	7.42	13.15	5.73	2.96	0.025	0.0225	**0.30**	**0.17**	**0.15**
31	23285	13.0	0.00055	119	9.43	13.60	4.17	2.15	0.025	0.0225	**0.08**	**0.05**	**0.03**
32	23515	13.0	0.00035	150	9.66	13.66	4.00	1.69	0.025	0.0225	**0.01**	**0.02**	**0.01**
33	24040	13.0	0.00035	115	10.22	13.83	3.61	1.45	0.03	0.0225	**0.00**	**0.01**	**0.00**
34	24530	13.0	0.00085	84	10.48	14.14	3.66	1.82	0.03	0.0225	**0.07**	**0.04**	**0.02**
35	25120	13.0	0.00130	79	10.88	15.21	4.33	3.45	0.025	0.0225	0.46	0.30	0.30
36	25601	13.0	0.00130	96	12.14	15.71	3.57	2.85	0.025	0.0225	0.38	0.19	0.20
37	26185	13.0	0.00220	71	12.49	16.15	3.66	3.64	0.025	0.0225	**0.79**	**0.51**	**0.77**
38	26610	13.0	0.00235	70	13.64	17.27	3.63	3.93	0.025	0.0225	**0.86**	**0.64**	**0.91**
39	27235	13.0	0.00100	123	15.11	18.23	3.12	2.31	0.025	0.0225	0.20	0.09	0.08
40	28025	13.0	0.00100	80	15.54	18.81	3.27	2.34	0.025	0.0225	0.15	0.06	0.06
41	28580	13.0	0.00175	132	16.94	19.96	3.02	2.94	0.025	0.0225	0.68	0.33	0.41
42	29550	17.0	0.00175	104	18.32	21.12	2.80	2.92	0.025	0.0225	0.39	0.18	0.17
43	30060	17.0	0.00175	92	19.24	22.79	3.55	2.96	0.025	0.0225	0.58	0.23	0.31
44	30785	17.0	0.00175	111	20.85	24.11	3.26	3.07	0.025	0.0225	0.58	0.26	0.29
45	31630	17.0	0.00175	99	22.21	24.27	2.06	1.94	0.03	0.0275	0.19	0.05	0.07
46	32170	17.0	0.00300	99	23.34	25.39	2.05	2.75	0.03	0.0275	0.64	0.21	0.35
47	32660	17.0	0.00250	127	24.62	28.05	3.43	3.65	0.03	0.0275	**1.54**	**0.78**	**1.22**
48	33405	17.0	0.00085	140	26.34	28.66	2.32	1.56	0.03	0.0275	**0.03**	**0.02**	**0.02**
49	33715	17.0	0.00155	158	27.33	28.99	1.66	1.68	0.03	0.0275	0.11	0.03	0.04
50	34440	17.0	0.00220	151	29.20	30.78	1.58	1.87	0.03	0.0275	0.27	0.06	0.10
51	34955	17.0	0.00220	131	29.55	31.98	2.43	2.36	0.03	0.0275	0.63	0.17	0.30
52	35695	17.0	0.00220	123	31.22	33.67	2.45	2.38	0.03	0.0275	0.61	0.16	0.29
53	36635	17.0	0.00220	140	32.90	35.67	2.77	2.02	0.04	0.0350	0.77	0.16	0.39
54	37275	17.0	0.00220	202	35.45	37.21	1.76	1.61	0.04	0.0350	0.39	0.07	0.15
55	38675	17.0	0.00220	85	37.55	39.95	2.40	1.83	0.04	0.0350	0.35	0.06	0.16
56	39475	17.0	0.00220	125	39.08	41.60	2.52	1.92	0.04	0.0350	0.56	0.11	0.26
57	40260	17.0	0.00220	104	40.38	43.64	3.26	2.17	0.04	0.0350	0.79	0.17	0.48
58	41660	17.0	0.00220	193	44.22	46.70	2.48	2.05	0.04	0.0350	0.84	0.19	0.39

Table 13 Whakatane River – bed material transport – 20 year return period flood flow

Cross section	Profile distance (m)	Bed material d50 (mm)	Energy slope	Channel width (m)	Mean Bed level (m)	Flood level (m)	Flood Depth (m)	Effective Velocity (m/s)	Resistance		Sediment transport		
									Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	11.72	6.13	3.11	0.025	0.0225	**0.32**	**0.19**	**0.17**
29	21355	13.0	0.00075	70	6.60	12.10	5.50	2.74	0.025	0.0225	**0.22**	**0.11**	**0.10**
30	22515	13.0	0.00075	88	7.42	13.38	5.96	3.08	0.025	0.0225	**0.32**	**0.19**	**0.16**
31	23285	13.0	0.00055	119	9.43	13.92	4.49	2.28	0.025	0.0225	**0.11**	**0.06**	**0.04**
32	23515	13.0	0.00035	150	9.66	13.98	4.32	1.80	0.025	0.0225	**0.02**	**0.02**	**0.01**
33	24040	13.0	0.00035	115	10.22	14.18	3.96	1.46	0.03	0.0225	**0.00**	**0.01**	**0.00**
34	24530	13.0	0.00085	84	10.48	14.53	4.05	1.97	0.03	0.0225	**0.09**	**0.05**	**0.03**
35	25120	13.0	0.00130	79	10.88	15.52	4.64	3.24	0.025	0.0225	0.53	0.30	0.37
36	25601	13.0	0.00130	96	12.14	15.99	3.85	2.96	0.025	0.0225	0.44	0.23	0.25
37	26185	13.0	0.00220	71	12.49	16.67	4.18	3.91	0.025	0.0225	**0.99**	**0.72**	**1.15**
38	26610	13.0	0.00235	70	13.64	17.72	4.08	4.20	0.025	0.0225	**1.05**	**0.88**	**1.29**
39	27235	13.0	0.00100	123	15.11	18.64	3.53	2.56	0.025	0.0225	0.27	0.13	0.11
40	28025	13.0	0.00100	80	15.54	19.08	3.54	2.42	0.025	0.0225	0.18	0.07	0.07
41	28580	13.0	0.00175	132	16.94	20.42	3.48	3.19	0.025	0.0225	0.89	0.49	0.63
42	29550	17.0	0.00175	104	18.32	21.68	3.36	2.97	0.025	0.0225	0.58	0.24	0.30
43	30060	17.0	0.00175	92	19.24	23.06	3.82	3.20	0.025	0.0225	0.67	0.30	0.39
44	30785	17.0	0.00175	111	20.85	24.30	3.45	3.23	0.025	0.0225	0.65	0.32	0.34
45	31630	17.0	0.00175	99	22.21	24.69	2.48	2.19	0.03	0.0275	0.30	0.08	0.12
46	32170	17.0	0.00300	99	23.34	25.77	2.43	3.11	0.03	0.0275	0.89	0.35	0.59
47	32660	17.0	0.00250	127	24.62	28.42	3.80	3.91	0.03	0.0275	**1.85**	**1.05**	**1.65**
48	33405	17.0	0.00085	140	26.34	29.04	2.70	1.75	0.03	0.0275	**0.06**	**0.03**	**0.03**
49	33715	17.0	0.00155	158	27.33	29.32	1.99	1.88	0.03	0.0275	0.20	0.06	0.07
50	34440	17.0	0.00220	151	29.20	30.93	1.73	2.00	0.03	0.0275	0.34	0.08	0.13
51	34955	17.0	0.00220	131	29.55	32.18	2.63	2.53	0.03	0.0275	0.74	0.21	0.39
52	35695	17.0	0.00220	123	31.22	33.86	2.64	2.55	0.03	0.0275	0.71	0.21	0.37
53	36635	17.0	0.00220	140	32.90	35.91	3.01	2.16	0.04	0.0350	0.91	0.21	0.50
54	37275	17.0	0.00220	202	35.45	37.47	2.02	1.77	0.04	0.0350	0.55	0.11	0.22
55	38675	17.0	0.00220	85	37.55	40.11	2.56	1.93	0.04	0.0350	0.40	0.08	0.19
56	39475	17.0	0.00220	125	39.08	41.80	2.72	2.03	0.04	0.0350	0.66	0.14	0.33
57	40260	17.0	0.00220	104	40.38	43.86	3.48	2.28	0.04	0.0350	0.90	0.21	0.58
58	41660	17.0	0.00220	193	44.22	46.98	2.76	2.21	0.04	0.0350	1.05	0.26	0.53

Table 14 Whakatane River – bed material transport – 50 year return period flood flow

Cross section	Profile distance (m)	Bed material d50 (mm)	Energy slope	Channel width (m)	Mean Bed level (m)	Flood level (m)	Flood Depth (m)	Effective Velocity (m/s)	Resistance		Sediment transport		
									Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	12.31	6.72	3.37	0.025	0.0225	**0.38**	**0.25**	**0.22**
29	21355	13.0	0.00075	70	6.60	12.75	6.15	3.00	0.025	0.0225	**0.28**	**0.15**	**0.15**
30	22515	13.0	0.00075	88	7.42	13.59	6.17	3.18	0.025	0.0225	**0.35**	**0.21**	**0.18**
31	23285	13.0	0.00055	119	9.43	14.26	4.83	2.42	0.025	0.0225	**0.13**	**0.07**	**0.05**
32	23515	13.0	0.00035	150	9.66	14.32	4.66	1.91	0.025	0.0225	**0.03**	**0.03**	**0.01**
33	24040	13.0	0.00035	115	10.22	14.56	4.34	1.55	0.03	0.0225	**0.00**	**0.01**	**0.00**
34	24530	13.0	0.00085	84	10.48	14.95	4.47	2.19	0.03	0.0225	**0.11**	**0.07**	**0.04**
35	25120	13.0	0.00130	79	10.88	15.79	4.91	3.44	0.025	0.0225	0.58	0.36	0.43
36	25601	13.0	0.00130	96	12.14	16.31	4.17	3.14	0.025	0.0225	0.52	0.29	0.32
37	26185	13.0	0.00220	71	12.49	17.11	4.62	4.32	0.025	0.0225	**1.18**	**1.03**	**1.55**
38	26610	13.0	0.00235	70	13.64	17.99	4.35	4.44	0.025	0.0225	**1.17**	**1.08**	**1.56**
39	27235	13.0	0.00100	123	15.11	19.01	3.90	2.79	0.025	0.0225	0.34	0.18	0.15
40	28025	13.0	0.00100	80	15.54	19.48	3.94	2.57	0.025	0.0225	0.22	0.10	0.10
41	28580	13.0	0.00175	132	16.94	20.88	3.94	3.57	0.025	0.0225	1.12	0.73	0.91
42	29550	17.0	0.00175	104	18.32	22.02	3.70	3.22	0.025	0.0225	0.70	0.33	0.40
43	30060	17.0	0.00175	92	19.24	23.25	4.01	3.36	0.025	0.0225	0.73	0.36	0.45
44	30785	17.0	0.00175	111	20.85	24.53	3.68	3.43	0.025	0.0225	0.74	0.39	0.41
45	31630	17.0	0.00175	99	22.21	24.94	2.73	2.38	0.03	0.0275	0.38	0.11	0.16
46	32170	17.0	0.00300	99	23.34	26.25	2.91	3.53	0.03	0.0275	1.25	0.59	1.01
47	32660	17.0	0.00250	127	24.62	28.87	4.25	4.22	0.03	0.0275	**2.26**	**1.44**	**2.31**
48	33405	17.0	0.00085	140	26.34	29.49	3.15	1.96	0.03	0.0275	**0.11**	**0.04**	**0.04**
49	33715	17.0	0.00155	158	27.33	29.73	2.40	2.18	0.03	0.0275	0.33	0.10	0.12
50	34440	17.0	0.00220	151	29.20	31.04	1.84	2.11	0.03	0.0275	0.39	0.10	0.15
51	34955	17.0	0.00220	131	29.55	32.40	2.85	2.71	0.03	0.0275	0.88	0.28	0.49
52	35695	17.0	0.00220	123	31.22	34.07	2.85	2.73	0.03	0.0275	0.83	0.27	0.46
53	36635	17.0	0.00220	140	32.90	36.17	3.27	2.32	0.04	0.0350	1.07	0.27	0.65
54	37275	17.0	0.00220	202	35.45	37.76	2.31	1.95	0.04	0.0350	0.75	0.16	0.33
55	38675	17.0	0.00220	85	37.55	40.29	2.74	2.05	0.04	0.0350	0.46	0.10	0.23
56	39475	17.0	0.00220	125	39.08	42.03	2.95	2.17	0.04	0.0350	0.78	0.18	0.42
57	40260	17.0	0.00220	104	40.38	44.13	3.75	2.44	0.04	0.0350	1.04	0.27	0.72
58	41660	17.0	0.00220	193	44.22	47.31	3.09	2.39	0.04	0.0350	1.32	0.36	0.75

Table 15 Whakatane River – bed material transport – 100 year return period flood flow

Cross section	Profile distance (m)	Bed material d50 (mm)	Energy slope	Channel width (m)	Mean Bed level (m)	Flood level (m)	Flood Depth (m)	Effective Velocity (m/s)	Resistance		Sediment transport		
									Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	12.72	7.13	3.55	0.025	0.0225	**0.43**	**0.31**	**0.26**
29	21355	13.0	0.00075	70	6.60	13.15	6.55	3.20	0.025	0.0225	**0.31**	**0.19**	**0.18**
30	22515	13.0	0.00075	88	7.42	13.83	6.41	3.28	0.025	0.0225	**0.38**	**0.24**	**0.21**
31	23285	13.0	0.00055	119	9.43	14.54	5.11	2.52	0.025	0.0225	**0.15**	**0.09**	**0.06**
32	23515	13.0	0.00035	150	9.66	14.60	4.94	2.00	0.025	0.0225	**0.04**	**0.03**	**0.02**
33	24040	13.0	0.00035	115	10.22	14.83	4.61	1.62	0.03	0.0225	**0.00**	**0.01**	**0.00**
34	24530	13.0	0.00085	84	10.48	15.23	4.75	2.32	0.03	0.0225	**0.13**	**0.09**	**0.05**
35	25120	13.0	0.00130	79	10.88	15.95	5.07	3.55	0.025	0.0225	0.62	0.41	0.48
36	25601	13.0	0.00130	96	12.14	16.49	4.35	3.27	0.025	0.0225	0.56	0.33	0.36
37	26185	13.0	0.00220	71	12.49	17.32	4.83	4.51	0.025	0.0225	**1.27**	**1.19**	**1.78**
38	26610	13.0	0.00235	70	13.64	18.16	4.52	4.60	0.025	0.0225	**1.25**	**1.23**	**1.75**
39	27235	13.0	0.00100	123	15.11	19.23	4.12	2.89	0.025	0.0225	0.38	0.21	0.18
40	28025	13.0	0.00100	80	15.54	19.75	4.21	2.73	0.025	0.0225	0.26	0.12	0.12
41	28580	13.0	0.00175	132	16.94	21.05	4.11	3.71	0.025	0.0225	1.21	0.84	1.03
42	29550	17.0	0.00175	104	18.32	22.20	3.88	3.38	0.025	0.0225	0.77	0.39	0.46
43	30060	17.0	0.00175	92	19.24	23.36	4.12	3.44	0.025	0.0225	0.77	0.39	0.49
44	30785	17.0	0.00175	111	20.85	24.66	3.81	3.54	0.025	0.0225	0.79	0.44	0.46
45	31630	17.0	0.00175	99	22.21	25.18	2.97	2.53	0.03	0.0275	0.45	0.14	0.21
46	32170	17.0	0.00300	99	23.34	26.63	3.29	3.84	0.03	0.0275	1.55	0.84	1.46
47	32660	17.0	0.00250	127	24.62	29.15	4.53	4.41	0.03	0.0275	**2.52**	**1.73**	**2.80**
48	33405	17.0	0.00085	140	26.34	29.78	3.44	2.09	0.03	0.0275	**0.15**	**0.06**	**0.05**
49	33715	17.0	0.00155	158	27.33	29.99	2.66	2.35	0.03	0.0275	0.43	0.14	0.17
50	34440	17.0	0.00220	151	29.20	31.14	1.94	2.20	0.03	0.0275	0.44	0.12	0.18
51	34955	17.0	0.00220	131	29.55	32.51	2.96	2.81	0.03	0.0275	0.94	0.31	0.55
52	35695	17.0	0.00220	123	31.22	34.20	2.98	2.84	0.03	0.0275	0.90	0.31	0.53
53	36635	17.0	0.00220	140	32.90	36.32	3.42	2.40	0.04	0.0350	1.17	0.31	0.74
54	37275	17.0	0.00220	202	35.45	37.93	2.48	2.06	0.04	0.0350	0.88	0.20	0.41
55	38675	17.0	0.00220	85	37.55	40.40	2.85	2.11	0.04	0.0350	0.50	0.11	0.26
56	39475	17.0	0.00220	125	39.08	42.16	3.08	2.25	0.04	0.0350	0.85	0.21	0.48
57	40260	17.0	0.00220	104	40.38	44.29	3.91	2.54	0.04	0.0350	1.12	0.31	0.82
58	41660	17.0	0.00220	193	44.22	47.51	3.29	2.49	0.04	0.0350	1.50	0.43	0.91

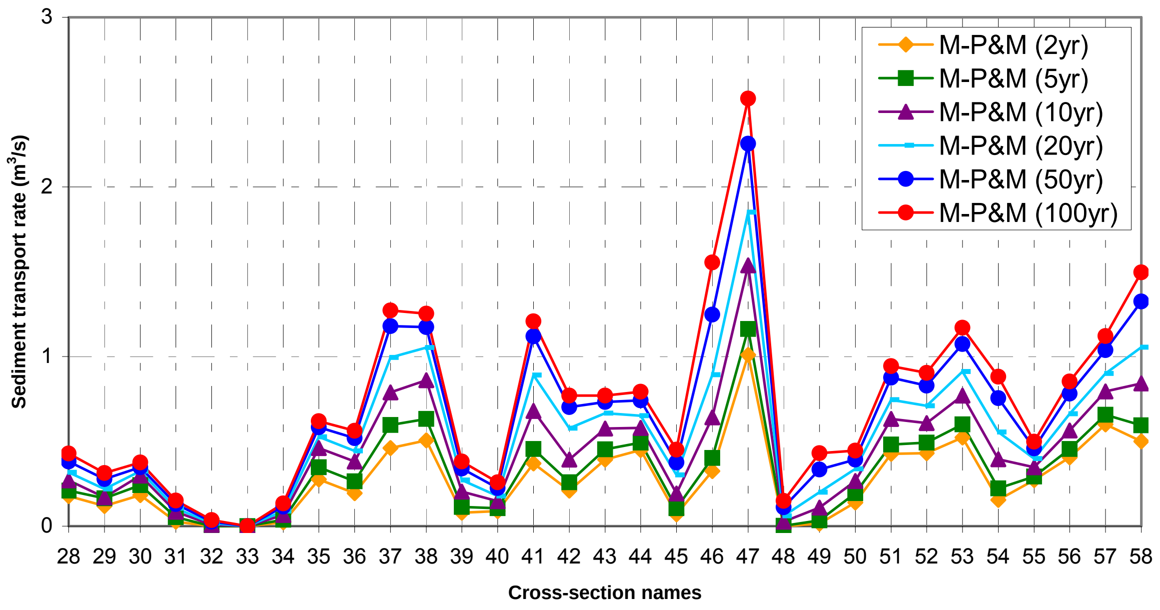

Figure 12 Whakatane River – Cross-sectional sediment transport rate estimated through Meyer-Peter & Muller formula

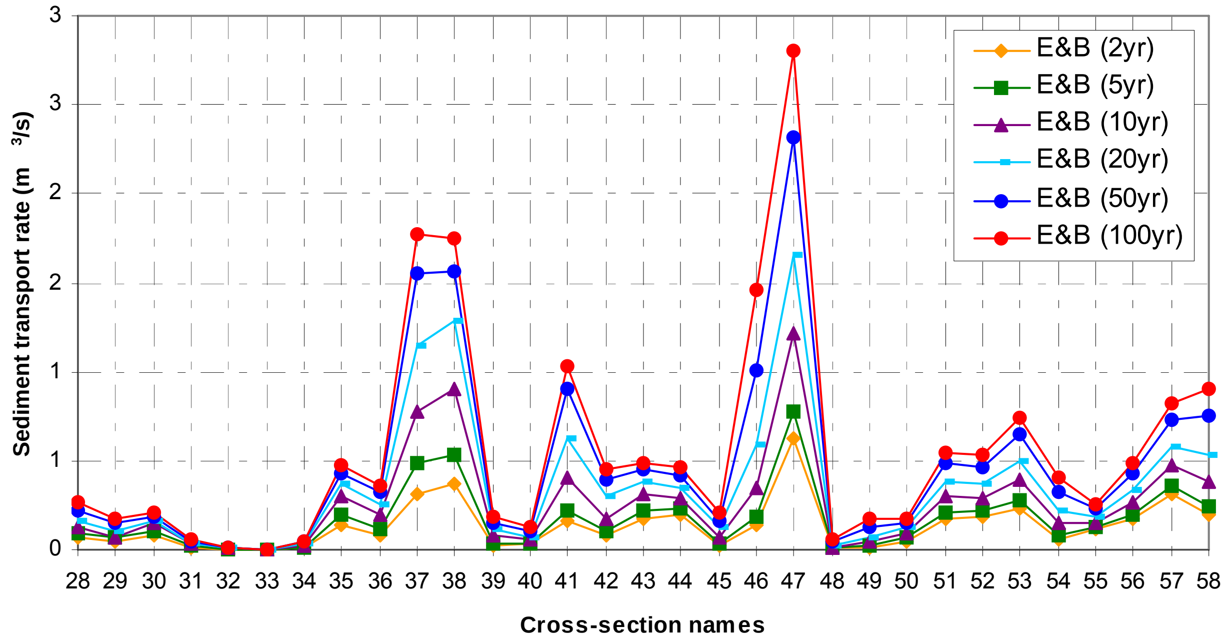

Figure 13 Whakatane River – Cross-sectional sediment transport rate estimated through the Einstein & Brown formula

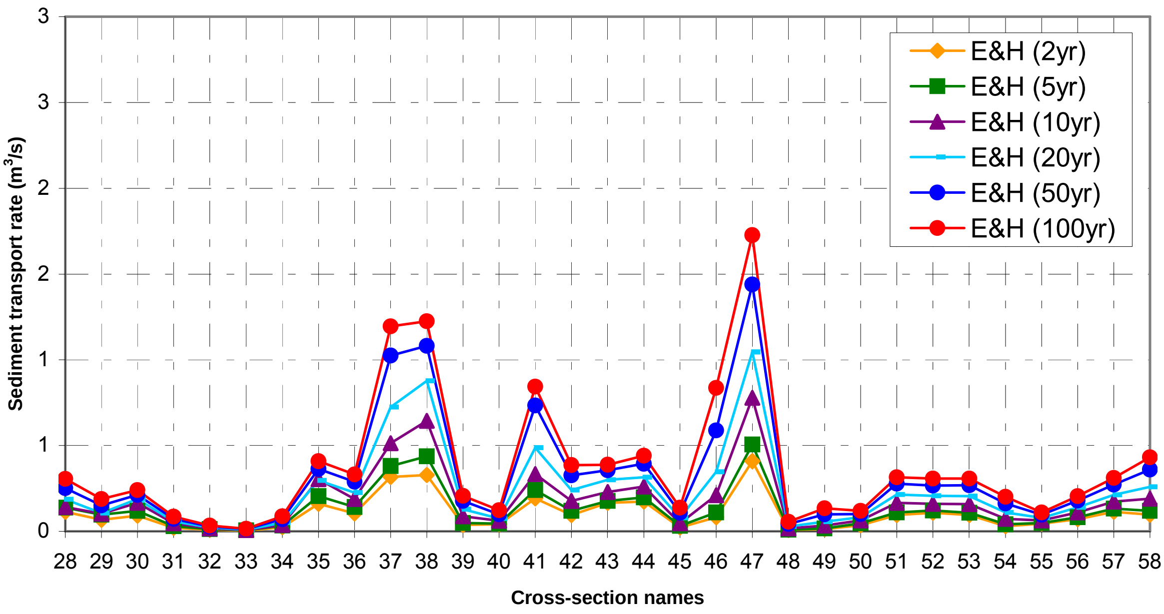

Figure 14 Whakatane River – Cross-sectional sediment transport rate estimated through the Engelund-Hansen formula

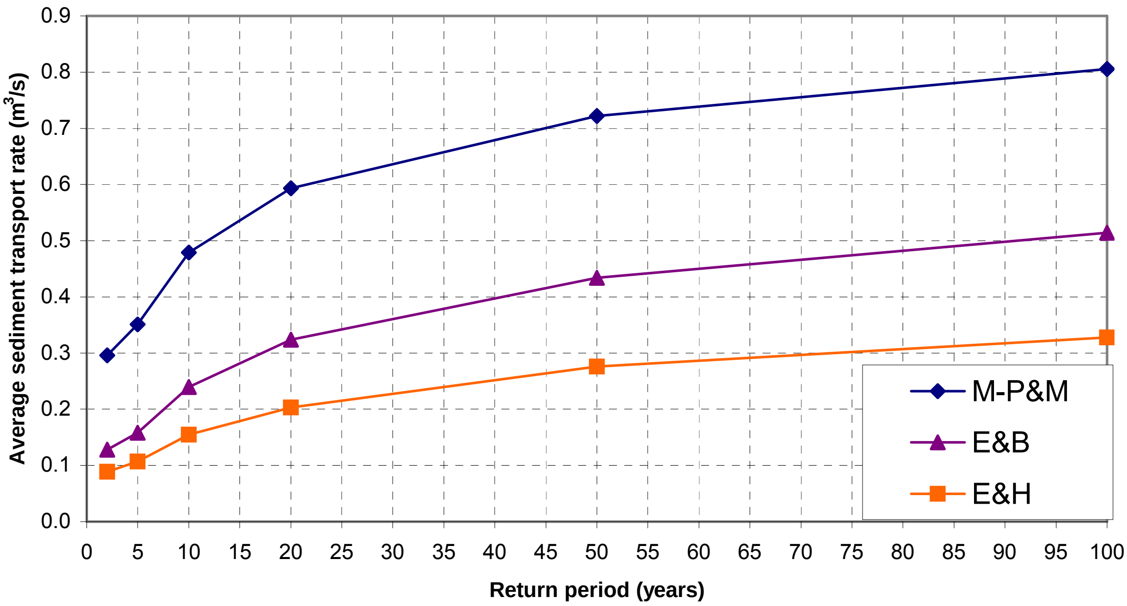

Figure 15 Average sediment transport rate over the Middle Reach of the Whakatane River (exclusive of outliers)

Table 16 Whakatane River – Average sediment transport rate over the middle reach of the river

Return Period (year)	Flow (m^3/s)	Meyer-Peter & Muller (m^3/s)	Engelund-Hansen (m^3/s)	Einstein-Brown (m^3/s)
2	530	0.30	0.09	0.13
5	620	0.35	0.11	0.16
10	860	0.48	0.15	0.24
20	1100	0.59	0.20	0.32
50	1410	0.72	0.28	0.43
100	1610	0.81	0.33	0.51

Note: The values in Table 16 are exclusive of outliers.

From Figure 15 above it is evident that the Engelund & Hansen formula (Equation 7.2) gives the lowest overall estimates over the studied reach of the river whereas the Meyer-Peter & Muller formula (Equation 7.1) gives the highest overall estimates (Figure 15). The Meyer-Peter & Muller formula estimate is up to more than three times the Engelund & Hansen formula estimate and up to more than two times the Einstein & Brown formula estimate. The Engelund & Hansen formula takes explicit account of both flow velocity and depth of flood as opposed to the other formulae. It can then be argued that its (Engelund & Hansen formula) results are more consistent with the variations reflecting changes in the river characteristics.

Between cross sections 34 to 30 where a marked change in grade occurred and the river is wider and shallower the transport rate is minimal. Immediately downstream of that stretch of the river the transport rate rises up again due to increased flow and gravel transported from the Waimana River.

7.3 Bed Transport Rates in the Whirinaki River

As for the Whakatane River, sediment transport rates were calculated at each river cross section, using flow levels, velocities, energy slopes and channel resistances at the sections, as given by the HEC-RAS hydraulic modelling of the river channel.

Representative flow depths, D, were used to calculate the unit transport rates at the sections, and this rate was then multiplied by the active width of the channel. Generally an average bed level across the main channel, where transport activity takes place, was used to determine the representative flow depths. This average bed level was determined in Hilltop and from cross-section plots, and is essentially the mean bed level of the channel, but excludes the bank itself and the higher part of the beach where there would be minimal transport activity. For some cross sections, where channel asymmetry or variations meant a single flow depth would not be representative, the active width was divided into two parts.

The grain resistance, n*, estimated from the size of the bed material was used as a guide in determining the active proportion of the channel resistance arising from the transport of bed material. However, in general the reach values of the channel resistance, n, determined through the hydraulic modelling were used, with a small and consistent reduction to account for the form resistance part, which would generally be the same along the river.

The grading curves from the bed material samples taken along the river channel (see Section 4.2) were used to determine an effective stone diameter, d_{50}. However, an average of the sample medium sizes was used, as the effective stone size should be representative of the bed material being transported along the reach.

The hydraulic modelling calculates energy slopes, s, at the model sections, but these slopes are derived from an iterated solution, and actual slopes along river reaches should be used. A profile plot of both bed and calculated water levels at the sections was used to determine where there were effective changes in slope, and reach gradients were then calculated from this data.

The hydraulic modelling assumes a fixed bed at each section and the resulting flow area and velocity values are not, therefore, always based on a realistic balancing of area (or flow depth) and velocity from section to section. Consequently the resulting transport rates must be averaged over a number of cross sections to give reach values.

Three empirical formulae were used to calculate the sediment transport rates, being the Meyer-Peter & Muller, Engelund & Hansen, and Einstein & Brown formulae. The results were calculated on a spreadsheet, and the input data and results for each section are given in Tables 17 to 23, and graphed on Figures 16 to 18, for flood flows of the estimated 2, 5, 10, 20, 50 and 100 year return period peak flow.

In the ‘sediment transport’ columns of Tables 17 to 23 no values were considered ‘outliers’, and all cross-sections were used to calculate average sediment transport rates.

Sediment transport rates for the middle reaches of the Whirinaki River are given in Table 24 and graphed on Figure 19. These values are based on an average of the calculated rates.

From Figure 19 it is obvious that the Engelund & Hansen formula (Equation 7.2) gives the lowest estimates whereas the Meyer-Peter & Mueller formula (Equation 7.1) gives the highest estimate (Figure 19). The transport rates given by the Meyer-Peter & Mueller formula are up to almost five times greater than those given by of the Engelund & Hansen formula, particularly for the shorter return period events. The Engelund & Hansen formula takes explicit account of both flow velocity and depth of flood as opposed to the other formulae.

Table 17 Whirinaki River – bed material transport – bank-full flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right		Left	Right	Left	Right	Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	175.49	1.39	0.69	1.67	1.18	0.035	0.0300	0.02	0.01	0.008
2	1520	0.023	0.0033	31		176.34		178.19	1.85		1.92		0.040	0.0350	0.14	0.02	0.055
3	2160	0.023	0.0039	36		178.70		180.08	1.38		1.83		0.040	0.0350	0.12	0.02	0.044
4	3160	0.023	0.0039	22		182.33		184.04	1.71		1.88		0.040	0.0350	0.12	0.02	0.051
5	4570	0.023	0.0033	43		188.00		189.47	1.47		1.62		0.045	0.0400	0.11	0.02	0.041
6	5870	0.023	0.0033	80		192.50		193.58	1.08		1.28		0.045	0.0400	0.08	0.01	0.031
7	6665	0.023	0.0038	37	42	195.50	195.80	196.45	0.95	0.65	1.63	1.34	0.035	0.0300	0.03	0.01	0.017
8	7210	0.023	0.0038	30		196.80		198.50	1.70		2.51		0.035	0.0300	0.14	0.04	0.058

Table 18 Whirinaki River – bed material transport – 2.33-year return period flood flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right		Left	Right	Left	Right	Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	175.69	1.59	0.89	1.84	1.37	0.035	0.0300	0.03	0.01	0.013
2	1520	0.023	0.0033	31		176.34		178.34	2.00		1.98		0.040	0.0350	0.17	0.03	0.070
3	2160	0.023	0.0039	36		178.70		180.22	1.52		1.92		0.040	0.0350	0.15	0.03	0.059
4	3160	0.023	0.0039	22		182.33		184.12	1.79		1.97		0.040	0.0350	0.13	0.02	0.059
5	4570	0.023	0.0033	43		188.00		189.62	1.62		1.72		0.045	0.0400	0.15	0.02	0.055
6	5870	0.023	0.0033	80		192.50		193.72	1.22		1.39		0.045	0.0400	0.12	0.02	0.044
7	6665	0.023	0.0038	37	42	195.50	195.80	196.53	1.03	0.73	1.72	1.45	0.035	0.0300	0.05	0.02	0.022
8	7210	0.023	0.0038	30		196.80		198.69	1.89		2.67		0.035	0.0300	0.18	0.06	0.080

Table 19 Whirinaki River – bed material transport – 5-year return period flood flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right						Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	175.94	1.84	1.14	2.07	1.63	0.035	0.0300	0.06	0.02	0.023
2	1520	0.023	0.0033	31		176.34		178.63	2.29		2.20		0.040	0.0350	0.22	0.04	0.105
3	2160	0.023	0.0039	36		178.70		180.54	1.84		2.17		0.040	0.0350	0.23	0.04	0.105
4	3160	0.023	0.0039	22		182.33		184.25	1.92		2.12		0.040	0.0350	0.16	0.03	0.072
5	4570	0.023	0.0033	43		188.00		189.73	1.73		1.79		0.045	0.0400	0.17	0.03	0.068
6	5870	0.023	0.0033	80		192.50		194.14	1.64		1.68		0.045	0.0400	0.28	0.04	0.107
7	6665	0.023	0.0038	37	42	195.50	195.80	196.65	1.15	0.85	1.86	1.60	0.035	0.0300	0.08	0.02	0.032
8	7210	0.023	0.0038	30		196.80		199.20	2.40		3.09		0.035	0.0300	0.30	0.11	0.163

Table 20 Whirinaki River – bed material transport – 10-year return period flood flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right						Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	176.15	2.05	1.35	2.23	1.81	0.035	0.0300	0.09	0.02	0.034
2	1520	0.023	0.0033	31		176.34		178.86	2.52		2.38		0.040	0.0350	0.27	0.06	0.140
3	2160	0.023	0.0039	36		178.70		180.80	2.10		2.39		0.040	0.0350	0.31	0.07	0.155
4	3160	0.023	0.0039	22		182.33		184.33	2.00		2.20		0.040	0.0350	0.17	0.03	0.082
5	4570	0.023	0.0033	43		188.00		190.30	2.30		2.05		0.045	0.0400	0.33	0.05	0.159
6	5870	0.023	0.0033	80		192.50		194.38	1.88		1.85		0.045	0.0400	0.39	0.06	0.161
7	6665	0.023	0.0038	37	42	195.50	195.80	196.84	1.34	1.04	2.06	1.81	0.035	0.0300	0.15	0.04	0.054
8	7210	0.023	0.0038	30		196.80		199.51	2.71		3.30		0.035	0.0300	0.38	0.15	0.235

Table 21 Whirinaki River – bed material transport – 20-year return period flood flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right						Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	176.33	2.23	1.53	2.39	1.98	0.035	0.0300	0.12	0.03	0.045
2	1520	0.023	0.0033	31		176.34		179.05	2.71		2.52		0.040	0.0350	0.32	0.07	0.174
3	2160	0.023	0.0039	36		178.70		181.04	2.34		2.59		0.040	0.0350	0.38	0.09	0.215
4	3160	0.023	0.0039	22		182.33		184.48	2.15		2.33		0.040	0.0350	0.20	0.04	0.102
5	4570	0.023	0.0033	43		188.00		190.48	2.48		2.05		0.045	0.0400	0.38	0.06	0.199
6	5870	0.023	0.0033	80		192.50		194.63	2.13		2.01		0.045	0.0400	0.52	0.08	0.234
7	6665	0.023	0.0038	37	42	195.50	195.80	196.99	1.49	1.19	2.21	1.98	0.035	0.0300	0.21	0.05	0.076
8	7210	0.023	0.0038	30		196.80		199.82	3.02		3.48		0.035	0.0300	0.47	0.19	0.325

Table 22 Whirinaki River – bed material transport – 50-year return period flood flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right						Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	176.54	2.44	1.74	2.56	2.16	0.035	0.0300	0.16	0.04	0.062
2	1520	0.023	0.0033	31		176.34		179.27	2.93		2.68		0.040	0.0350	0.37	0.09	0.220
3	2160	0.023	0.0039	36		178.70		181.31	2.61		2.80		0.040	0.0350	0.47	0.12	0.298
4	3160	0.023	0.0039	22		182.33		184.66	2.33		2.49		0.040	0.0350	0.23	0.05	0.129
5	4570	0.023	0.0033	43		188.00		190.78	2.78		2.11		0.045	0.0400	0.48	0.07	0.280
6	5870	0.023	0.0033	80		192.50		194.92	2.42		2.19		0.045	0.0400	0.68	0.12	0.344
7	6665	0.023	0.0038	37	42	195.50	195.80	197.17	1.67	1.37	2.39	2.17	0.035	0.0300	0.29	0.08	0.110
8	7210	0.023	0.0038	30		196.80		200.14	3.34		3.66		0.035	0.0300	0.56	0.25	0.439

Table 23 Whirinaki River – bed material transport – 100-year return flood flow

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Flood level (m)	Flood depth (m)		Effective velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right						Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	176.68	2.58	1.88	2.67	2.28	0.035	0.0300	0.18	0.05	0.076
2	1520	0.023	0.0033	31		176.34		179.43	3.09		2.79		0.040	0.0350	0.41	0.11	0.258
3	2160	0.023	0.0039	36		178.70		181.51	2.81		2.95		0.040	0.0350	0.54	0.15	0.372
4	3160	0.023	0.0039	22		182.33		184.78	2.45		2.59		0.040	0.0350	0.26	0.06	0.150
5	4570	0.023	0.0033	43		188.00		190.89	2.89		2.17		0.045	0.0400	0.52	0.08	0.315
6	5870	0.023	0.0033	80		192.50		195.12	2.62		2.30		0.045	0.0400	0.80	0.15	0.436
7	6665	0.023	0.0038	37	42	195.50	195.80	197.30	1.80	1.50	2.52	2.30	0.035	0.0300	0.35	0.10	0.141
8	7210	0.023	0.0038	30		196.80		200.30	3.50		3.77		0.035	0.0300	0.61	0.28	0.506

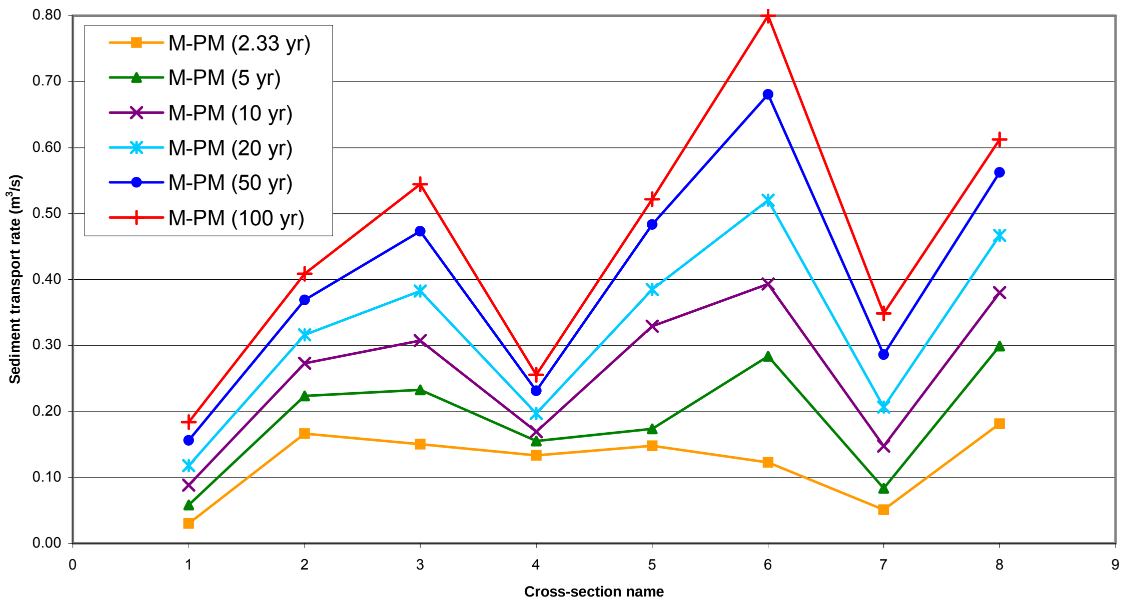

Figure 16 Cross-sectional sediment transport rate estimated through the Meyer-Peter & Muller formula – Whirinaki River

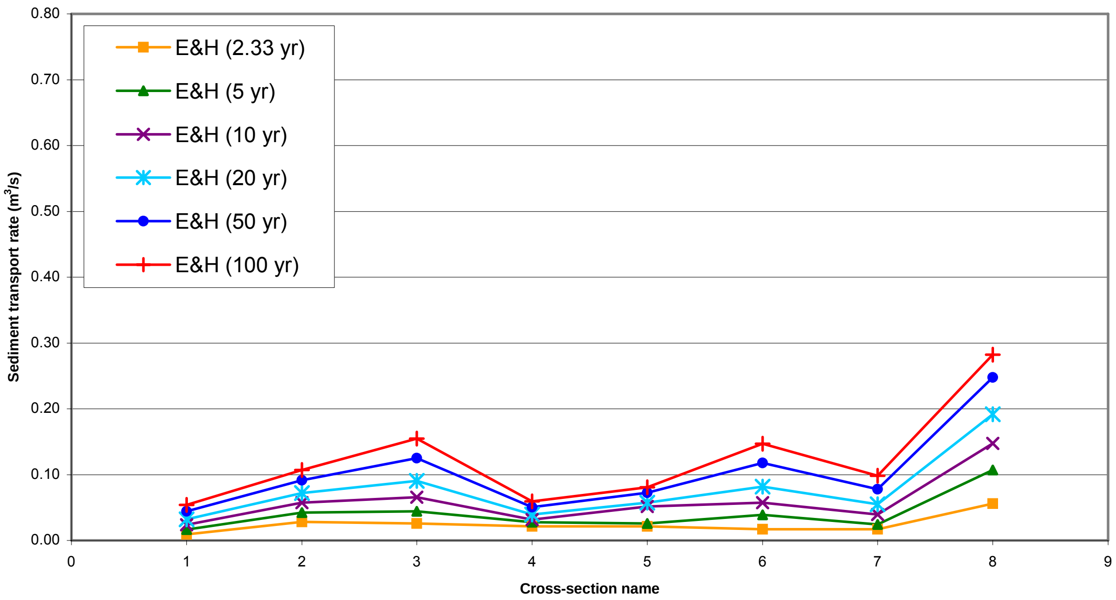

Figure 17 Cross-sectional sediment transport rate estimated through the Engelund-Hansen formula – Whirinaki River

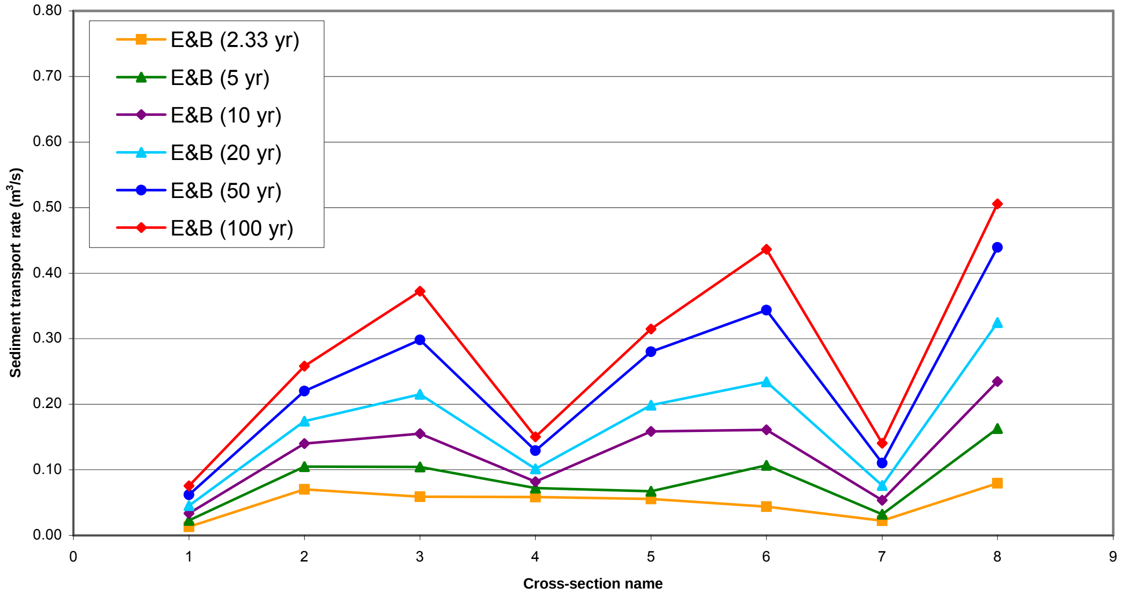

Figure 18 Cross-sectional sediment transport rate estimated through the Einstein-Brown formula – Whirinaki River

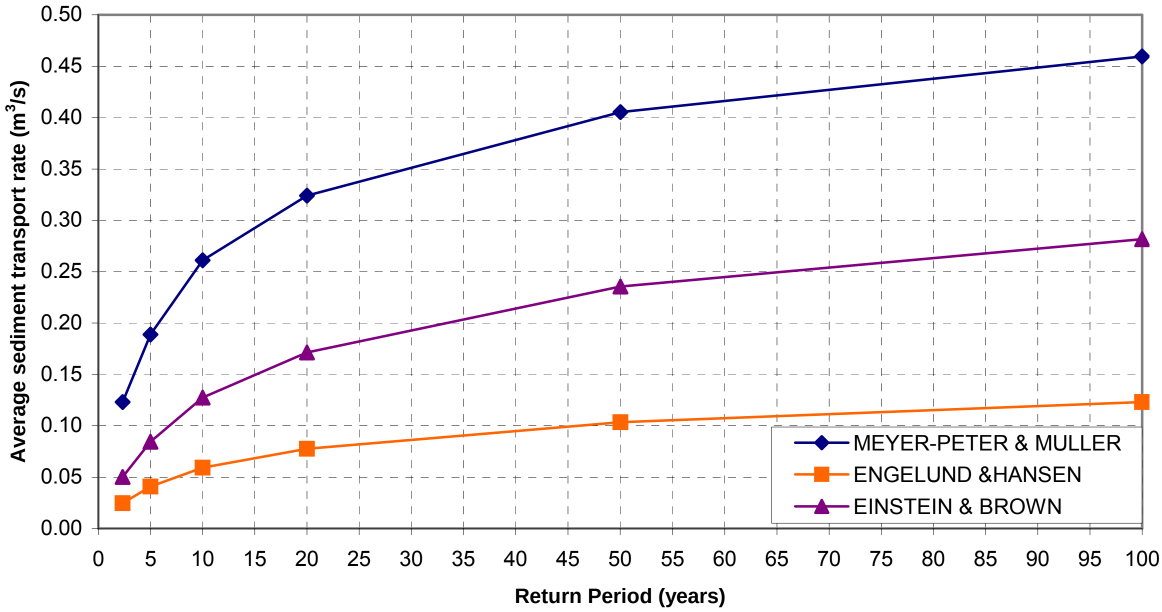

Figure 19 Average sediment transport rate over the Lower Reach of the Whirinaki River

Table 24 Whirinaki River – Average Sediment Transport Rates

Return Period (year)	Flow (cumecs)	Meyer-Peter & Muller (m^3/s)	Engelund-Hansen (m^3/s)	Einstein-Brown (m^3/s)
2.33yr	120	0.123	0.025	0.050
5yr	174	0.189	0.041	0.084
10yr	226	0.261	0.059	0.127
20yr	277	0.324	0.078	0.171
50yr	343	0.405	0.103	0.235
100yr	392	0.459	0.123	0.282

7.4 Bed Transport Rating in the Whakatane River

The calculated average transport rates for the 2, 5, 10, 20, 50 and 100 year flood flows (Figure 15 and Table 16) can be used to develop a simple power relationship between flow and bed material transport. This is achieved by fitting a straight line to a log-log plot of the flows versus their corresponding average transport rate values as recorded in Table 16. The results for the Meyer-Peter & Muller, Engelund & Hansen and the Einstein & Brown formulae are graphed in Figure 20. The transport ratings as a function of flow in the channel are translated as:

- From the Meyer-Peter & Muller results $Y = 0.0011Q^{0.8947}$ (R^2=0.9976) (7.4)
- From the Engelund & Hansen results $Y = 0.00006Q^{1.1626}$ (R^2=0.9995) (7.5)
- From the Einstein & Brown results $Y = 0.00005Q^{1.2446}$ (R^2=0.9997) (7.6)

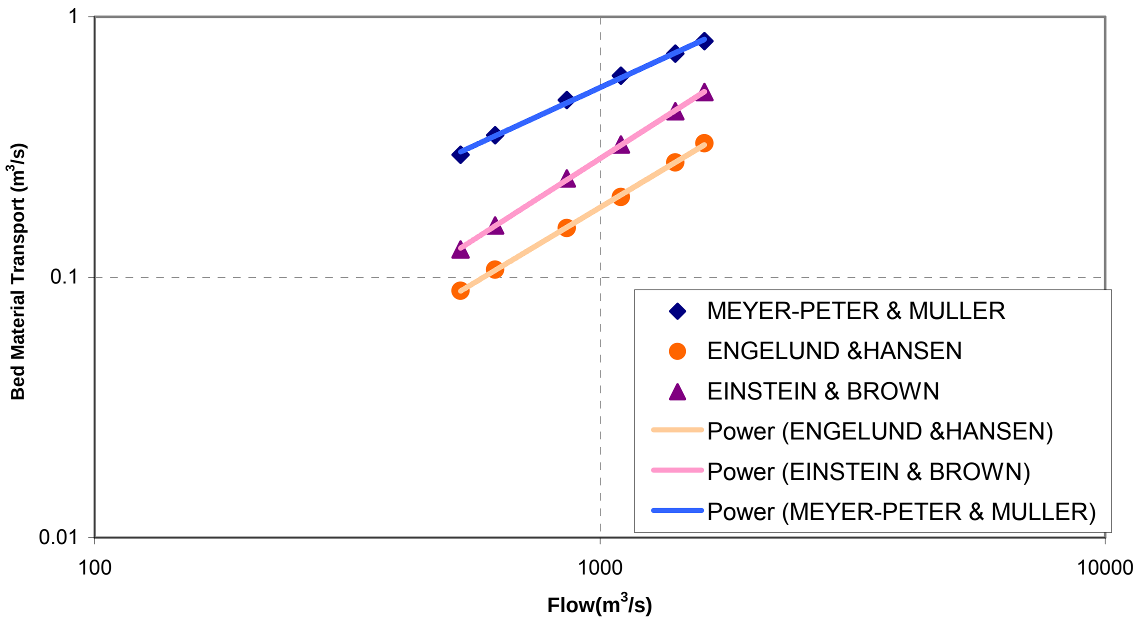

Figure 20 Transport ratings in the middle reach of the Whakatane River – not accounting for the threshold flow at which motion of gravel starts

However, these relationships do not consider the threshold flow at which gravel movement starts. The notion that some critical or threshold level of flow, velocity or a related parameter must be attained before the gravel on a channel bed will start to move downstream has long been implanted in the literature of hydraulics. Early research tended to focus on a critical velocity as a function of particle size. However, because of the variability of the critical velocity with flow depth (D) for beds of given particle size, attention subsequently turned to the use of the tractive stress as a predictor of the onset of entrainment. The tractive stress is the dragging force of the flow on the channel boundary per unit area of the boundary. Under that definition, Shield examined in 1936 the relationship between the critical tractive stress for bed material movement and particle diameter and derived for hydro-dynamically rough surfaces (e.g., gravel beds) a critical depth, D_c, for entrainment as:

$$D_c = \frac{d_{50}}{11s}$$

From Manning's equation the critical mean velocity, $v_{mc} = \frac{D_c^{0.67} s^{0.5}}{n}$, for the onset of motion is obtained.

The threshold or critical bed transport rating using the critical depth and velocity are computed using the Meyer-Peter & Muller, Engelund & Hansen and the Einstein & Brown formulae. The results are in Table 25 and Figure 21. The critical flow for the start of motion of gravel in the Whakatane River is in the range of 95 cumecs. The flow of 95 m^3/s is obtained by incrementally increasing and/or decreasing flow at the upstream boundary of the HEC-RAS model until the critical water level was obtained. This flow means that bed material movement occurred during less significant flood events (including average size freshes) and possibly several times a year. This is an expected phenomenon.

Table 25 Whakatane River – bed material transport – critical mean flow for onset of motion

Cross section	Profile distance (m)	Bed material d50 (mm)	Energy slope	Channel width (m)	Mean Bed level (m)	Critical Depth (m)	Critical Velocity (m/s)	Resistance		Sediment transport		
								Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
28	20595	13.0	0.00075	81	5.59	1.57576	0.92554	0.025	0.0225	0.000	0.006	0.003
29	21355	13.0	0.00075	70	6.60	1.57576	0.92554	0.025	0.0225	0.000	0.005	0.002
30	22515	13.0	0.00075	88	7.42	1.57576	0.92554	0.025	0.0225	0.000	0.006	0.003
31	23285	13.0	0.00055	119	9.43	2.14876	0.92554	0.025	0.0225	0.000	0.009	0.004
32	23515	13.0	0.00035	150	9.66	3.37662	0.92554	0.025	0.0225	0.000	0.013	0.005
33	24040	13.0	0.00035	115	10.22	3.37662	0.92554	0.03	0.0225	0.000	0.007	0.002
34	24530	13.0	0.00085	84	10.48	1.39037	0.92554	0.03	0.0225	0.000	0.004	0.001
35	25120	13.0	0.00130	79	10.88	0.90909	0.92554	0.025	0.0225	0.000	0.005	0.003
36	25601	13.0	0.00130	96	12.14	0.90909	0.92554	0.025	0.0225	0.000	0.005	0.003
37	26185	13.0	0.00220	71	12.49	0.53719	0.92554	0.025	0.0225	0.000	0.003	0.002
38	26610	13.0	0.00235	70	13.64	0.50290	0.92554	0.025	0.0225	0.000	0.003	0.002
39	27235	13.0	0.00100	123	15.11	1.18182	0.92554	0.025	0.0225	0.000	0.008	0.004
40	28025	13.0	0.00100	80	15.54	1.18182	0.92554	0.025	0.0225	0.000	0.005	0.003
41	28580	13.0	0.00175	132	16.94	0.67532	0.92554	0.025	0.0225	0.000	0.007	0.005
42	29550	17.0	0.00175	104	18.32	0.88312	0.92554	0.025	0.0225	0.000	0.009	0.005
43	30060	17.0	0.00175	92	19.24	0.88312	0.92554	0.025	0.0225	0.000	0.009	0.005
44	30785	17.0	0.00175	111	20.85	0.88312	0.92554	0.025	0.0225	0.000	0.009	0.006
45	31630	17.0	0.00175	99	22.21	0.88312	0.92554	0.03	0.0275	0.000	0.006	0.006
46	32170	17.0	0.00300	99	23.34	0.51515	0.92554	0.03	0.0275	0.000	0.005	0.006
47	32660	17.0	0.00250	127	24.62	0.61818	0.92554	0.03	0.0275	0.000	0.007	0.007
48	33405	17.0	0.00085	140	26.34	1.81818	0.92554	0.03	0.0275	0.000	0.010	0.008
49	33715	17.0	0.00155	158	27.33	0.99707	0.92554	0.03	0.0275	0.000	0.010	0.009
50	34440	17.0	0.00220	151	29.20	0.70248	0.92554	0.03	0.0275	0.000	0.008	0.008
51	34955	17.0	0.00220	131	29.55	0.70248	0.92554	0.03	0.0275	0.000	0.007	0.007
52	35695	17.0	0.00220	123	31.22	0.70248	0.92554	0.03	0.0275	0.000	0.007	0.007
53	36635	17.0	0.00220	140	32.90	0.70248	0.92554	0.04	0.0350	0.000	0.004	0.006
54	37275	17.0	0.00220	202	35.45	0.70248	0.92554	0.04	0.0350	0.000	0.006	0.009
55	38675	17.0	0.00220	85	37.55	0.70248	0.92554	0.04	0.0350	0.000	0.005	0.007
56	39475	17.0	0.00220	125	39.08	0.70248	0.92554	0.04	0.0350	0.000	0.004	0.006
57	40260	17.0	0.00220	104	40.38	0.70248	0.92554	0.04	0.0350	0.000	0.003	0.005
58	41660	17.0	0.00220	193	44.22	0.70248	0.92554	0.04	0.0350	0.000	0.006	0.009
Average										*0.000*	*0.007*	*0.005*

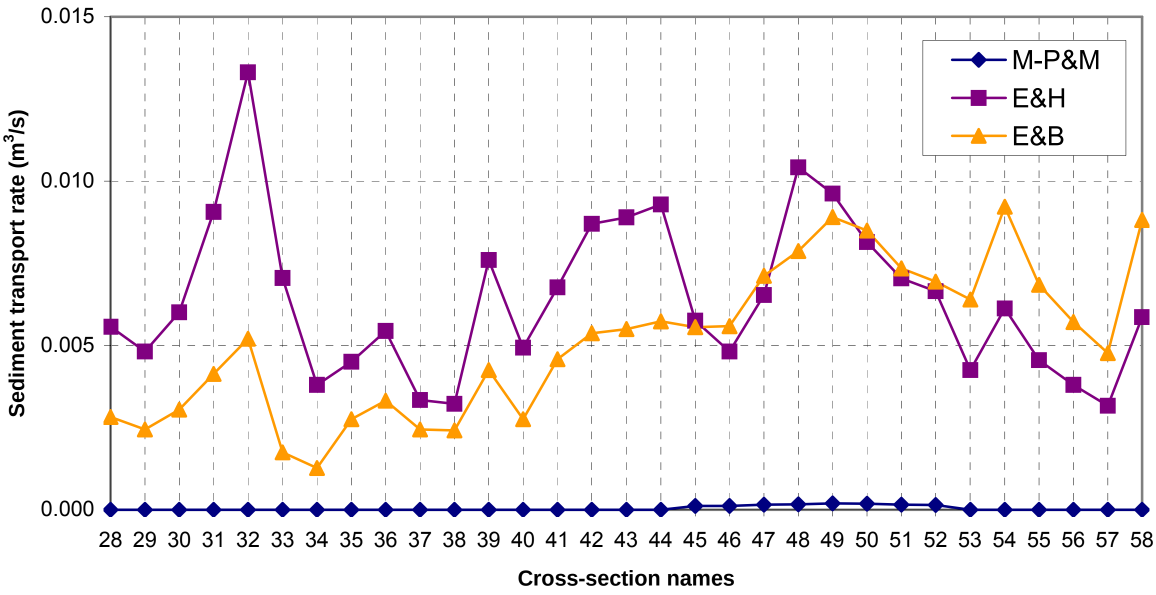

Figure 21 Whakatane River – Cross-sectional sediment transport rate estimated using the critical flow depth and velocity

The Meyer-Peter & Muller formula gives the lowest estimates. This is expected since the Meyer-Peter & Muller formula explicitly uses the Shields criterion and hence little if any sediment transport occurs at the threshold or critical flow.

Data points for the transport rating are plotted in Figure 22. A power relationship curve gives a very skewed trend line at the lower end of the rating (i.e., does not give a good fit) through the data points. Consequently, to derive more accurately the transport rate formulae a polynomial relationship of order 3 was introduced. Thus, two sets of equations are proposed for the rating:

For $95m^3/s \le Q \le 550m^3/s$

- From the Meyer-Peter & Muller results

$$Y = 5 \times 10^{-11} \times Q^3 - 3 \times 10^{-7} \times Q^2 + 0.0008 \times Q - 0.0764 \quad (R^2=1) \quad (7.7)$$

- From the Engelund & Hansen results

$$Y = 2 \times 10^{-11} \times Q^3 - 2 \times 10^{-8} \times Q^2 + 0.0002 \times Q - 0.0123 \quad (R^2=1) \quad (7.8)$$

- From the Einstein & Brown results

$$Y = -1 \times 10^{-11} \times Q^3 + 7 \times 10^{-8} \times Q^2 + 0.0002 \times Q - 0.0189 \quad (R^2=0.9999) \quad (7.9)$$

For $Q \ge 550m^3/s$

- From the Meyer-Peter & Muller results

$$Y = 0.0011Q^{0.8947} \quad (R^2=0.9976) \quad (7.4)$$

- From the Engelund & Hansen results

$$Y = 0.00006Q^{1.1626} \qquad (R^2=0.9995) \qquad (7.5)$$

- From the Einstein & Brown results

$$Y = 0.00005Q^{1.2446} \qquad (R^2=0.9997) \qquad (7.6)$$

Where *Y* is the sediment transport rate in m^3/s, *Q* is the flow rate in m^3/s, and R^2 is the coefficient of correlation.

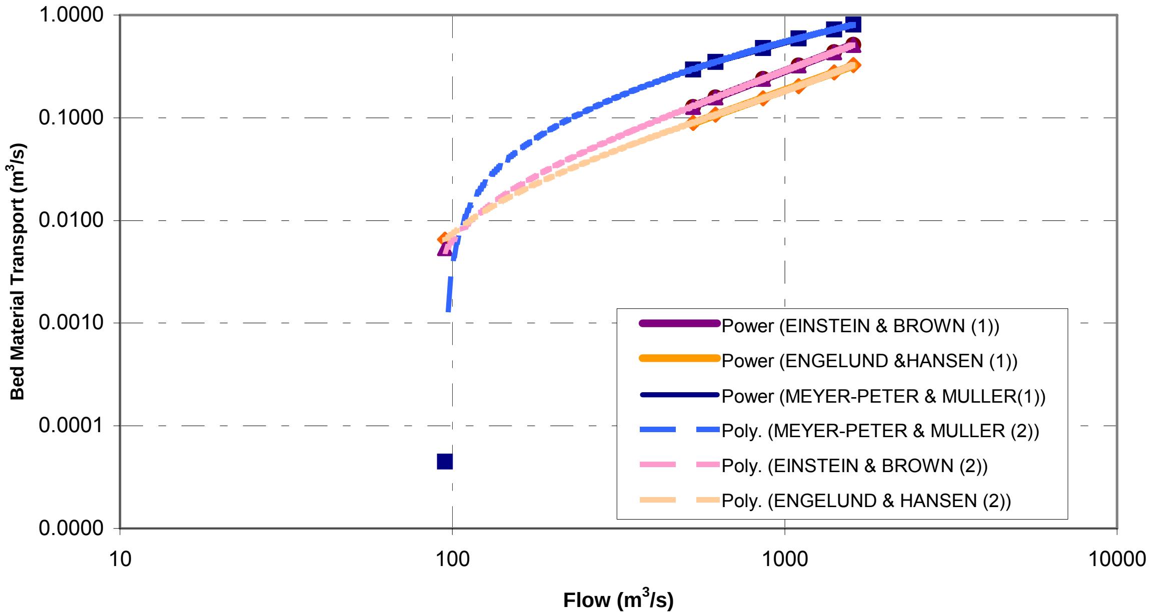

Figure 22 *Transport ratings in the middle reach of the Whakatane River – including threshold of motion flow. Polynomial relationship derived plot*

Figure 22 shows the power relationships derived in Figure 20 as well as the polynomial relationship derived by including the threshold of motion data.

It is worthwhile noting that the threshold of motion flow, thus the critical tractive stress, varies according to the duration between floods. If two successive floods are separated by a long low flow period, then there will be sufficient amount of time available for the ingress of fine sediment and small size rock particles into the voids of larger size rock particles. Floods occurring after such long periods of low water will certainly require significantly higher critical tractive stress to initiate bed material movement.

From Figure 22 above it is obvious that for flow greater than $95m^3/s$ and lower than $550m^3/s$ Equations 7.7 to 7.9 are best suited to estimate the bed material transport rate in the middle reach of the Whakatane River. For flow greater than $550m^3/s$ it is recommended to use Equations 7.4 to 7.6.

7.5 Bed Transport Rating in the Whirinaki River

As with the Whakatane River, two sets of bed material transport ratings are proposed. Firstly, the calculated transport rates for the design 2, 5, 10, 20, 50 and 100 year flood flows are used to develop a power relationship between flow and bed material transport for flows greater than the 2 year flood. Using an average transport over the studied reach a straight line is fitted to a log plot of the flows versus the average transport rate values. The results for the Meyer-Peter & Muller, Engelund & Hansen and the Einstein & Brown formulae are in Figure 23.

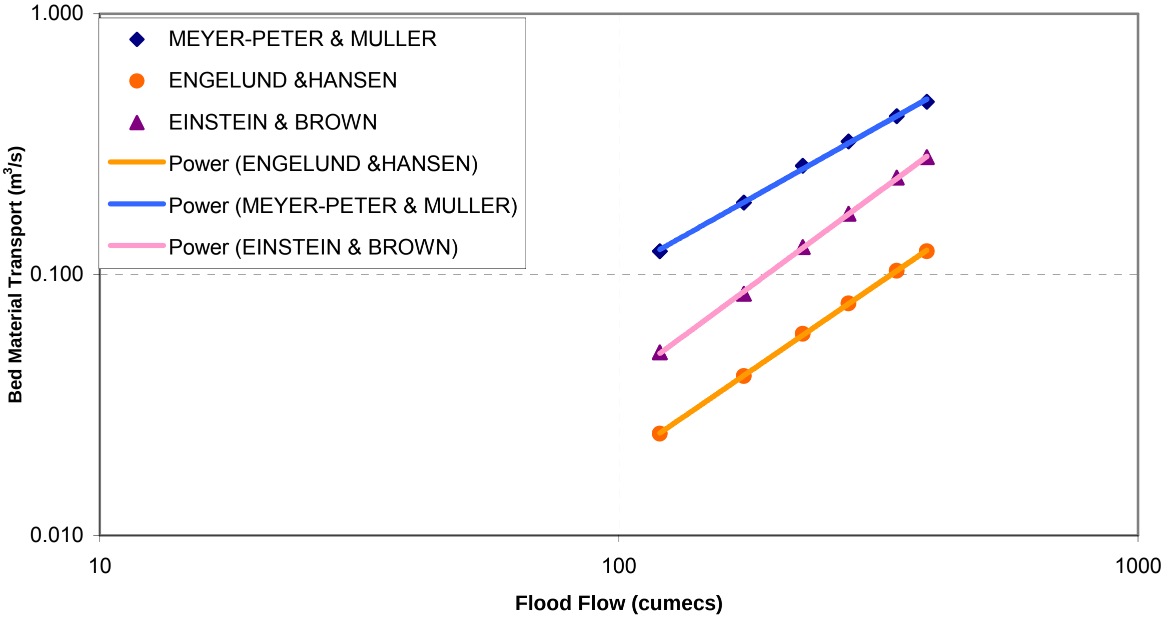

Figure 23 Transport ratings in the lower reach of the Whirinaki River – excluding threshold of motion flow

The threshold or critical bed transport rates using the critical depth and velocity are computed using the Meyer-Peter & Muller, Engelund & Hansen and the Einstein & Brown formulae. The results are in Table 26 and Figure 24. The critical flow for the start of motion of gravel in the Whirinaki River is in the range of 25 cumecs. The flow of 25 m^3/s was obtained by incrementally increasing and/or decreasing flow at the upstream boundary of the HEC-RAS model until the critical water levels at each cross section were matched. As with the Whakatane River estimates, accurate solutions can only be obtained with the polynomial relationship of order 3 for the Meyer-Peter & Muller formula. The Meyer-Peter & Muller formula estimates nil transport rate of material. A zero value cannot be graphed on a log-log paper and therefore a log-linear graph was used.

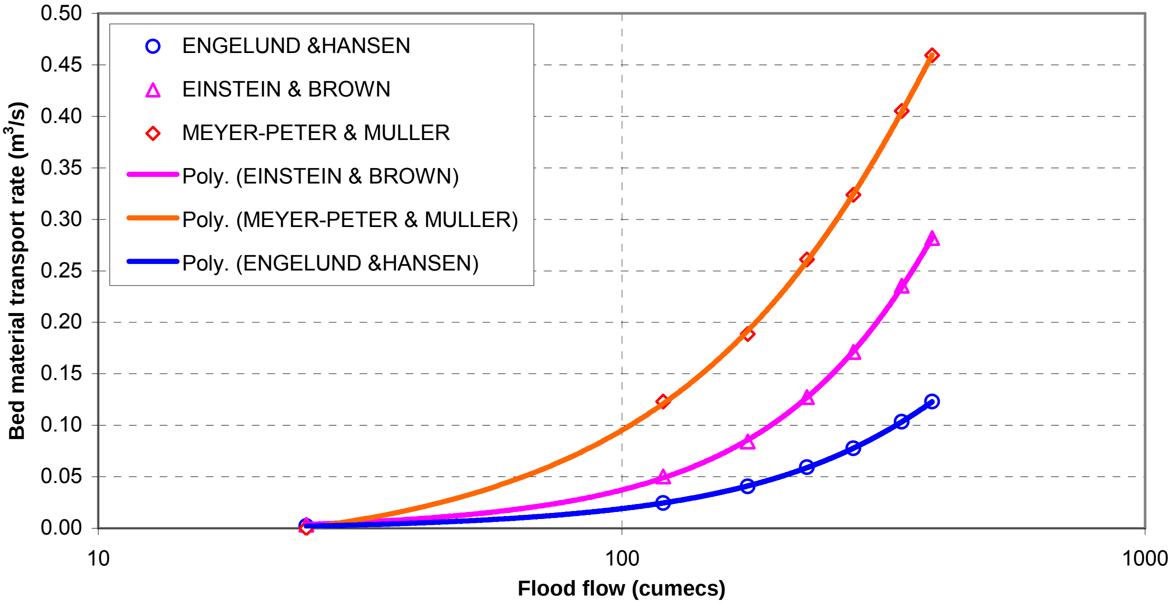

Figure 24 Transport ratings in the lower reach of the Whirinaki River – including threshold of motion flow

The two sets of equations proposed are as follows:

For $25m^3/s \le Q \le 120m^3/s$

- For the Meyer-Peter & Muller formula:

$$Y = -1\times 10^{-9}\times Q^3 + 7\times 10^{-7}\times Q^2 + 0.0012\times Q \;\; - 0.0299 \quad (R^2=0.9999) \quad (7.13)$$

- For the Engelund & Hansen formula:

$$Y = -6\times 10^{-10}\times Q^3 + 6\times 10^{-7}\times Q^2 + 0.0002\times Q \;\; - 0.0022 \quad (R^2=1) \quad (7.14)$$

- For the Einstein & Brown formula:

$$Y = -2\times 10^{-9}\times Q^3 + 2\times 10^{-6}\times Q^2 + 0.0002\times Q \;\; - 0.0032 \quad (R^2=0.9999) \quad (7.15)$$

For $Q \ge 120m^3/s$

- For the Meyer-Peter & Muller $Y = 0.0006Q^{1.1217}$ (R^2=0.9985) (7.10)
- For the Engelund & Hansen $Y = 0.00004Q^{1.3634}$ (R^2=0.9998) (7.11)
- For the Einstein & Brown $Y = 0.00004Q^{1.4696}$ (R^2=0.9997) (7.12)

R^2 represents the coefficient of correlation. Y and Q are in m^3/s.

Table 26 Whirinaki River – bed material transport – Critical mean flow for onset of motion

Cross section	Distance from confluence (m)	Bed material d50 (m)	Energy slope	Channel width (m)		Mean bed level (m)		Critical depth (m)		Critical velocity (m/s)		Resistance		Sediment transport		
				Left	Right	Left	Right					Bed	Grain	M-P&M (m^3/s)	E-H (m^3/s)	E-B (m^3/s)
1	570	0.023	0.0029	14	29	174.10	174.80	0.72	0.00	1.26	0.00	0.035	0.0300	0.18	0.05	0.076
2	1520	0.023	0.0033	31		176.34		0.63		1.10		0.040	0.0350	0.41	0.11	0.258
3	2160	0.023	0.0039	36		178.70		0.54		1.03		0.040	0.0350	0.54	0.15	0.372
4	3160	0.023	0.0039	22		182.33		0.54		1.01		0.040	0.0350	0.26	0.06	0.150
5	4570	0.023	0.0033	43		188.00		0.63		0.95		0.045	0.0400	0.52	0.08	0.315
6	5870	0.023	0.0033	80		192.50		0.63		1.00		0.045	0.0400	0.80	0.15	0.436
7	6665	0.023	0.0038	37	42	195.50	195.80	0.55	0.05	1.11		0.035	0.0300	0.35	0.10	0.141
8	7210	0.023	0.0038	30		196.80		0.55		1.30	0.00	0.035	0.0300	0.61	0.28	0.506

7.6 Total Bed Transport in the Whakatane River

Estimates of the amount of bed material transported down the Whakatane River were obtained by applying the transport rating curves (Equations 7.4, 7.5, 7.6; Figure 20 and equations 7.7, 7.8, 7.9; Figure 22) to available flood flow records. Flows were generated by applying flow rating curves to continuous water level records at recorder sites. The Whakatane River flows above the confluence of the Whakatane and Waimana Rivers are obtained by subtracting the recorded Waimana River at the Gorge flows from the recorded Whakatane River at Valley Road flows. Theses flows are generally recorded at 15 minutes intervals. Owing to the distance between Valley Road and Waimana Gorge recorders a time lag correction of 4.5 hours was applied to the Valley Road data to get a more accurate estimate of flows in the Upper Whakatane. Hence:

$Q_{\text{Upper Whakatane}}$ (at time t) = $Q_{\text{Valley Road}}$ (at time t plus 4.5 hrs) – $Q_{\text{Waimana Gorge}}$ (at time t)

Table 26 shows the average monthly flows of continuous flow data. Note that the Waimana Gorge recorder is not a permanently rated site and the flows are based on an old rating with limited gauging calibration. Accuracy of the flows for the Upper Whakatane River derived from Waimana Gorge flows is therefore limited.

The monthly means of the calculated continuous transport rates are given in Tables 27 to 29. Those values where obtained by applying the equations derived through the power relationship to flow values greater than 550m^3/s (Equations 7.4, 7.5, 7.6) and the equations derived through the polynomial relationship (Equations 7.7, 7.8, 7.9) to all flow values less than 550m^3/s but greater than 95m^3/s. Zero transport was assumed for any flow less than 95m^3/s. In the tables, the "?" mark represents months with missing average flow data. In order to have continuous monthly mean flows any gaps in the time series have been deleted where the flow is below the sediment threshold of 95m^3/s. Into any gaps which are above this threshold synthetic data has been inserted.

Table 26 Mean monthly flows (in m^3/s) on the Whakatane River upstream of the confluence with the Waimana River

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
1981	24.8	13.8	20.7	27.5	37.1	62.7	61.1	66.7	26.3	37.4	76.0	39.2	41.3
1982	26.7	27.9	31.0	25.0	28.6	49.7	24.2	20.5	20.3	14.6	8.2	10.2	23.9
1983	7.2	4.9	3.4	16.7	16.1	23.7	38.4	30.9	33.7	113.5	68.4	77.0	36.4
1984	27.2	62.7	55.8	22.7	14.0	17.9	50.0	32.4	29.4	21.7	13.4	43.2	32.5
1985	33.6	15.2	16.6	34.8	24.0	49.5	41.3	38.2	68.0	20.3	27.9	43.5	34.4
1986	57.3	13.3	35.7	12.7	34.9	42.3	42.0	78.6	62.3	25.4	15.3	12.4	36.2
1987	21.9	8.0	17.2	31.5	18.1	27.1	13.1	35.1	15.8	19.3	36.9	40.6	23.8
1988	12.8	11.8	20.5	3.8	13.3	20.6	40.3	57.9	37.1	30.9	29.9	40.3	26.7
1989	90.6	35.3	9.0	3.1	20.1	68.9	61.8	18.1	38.7	88.7	33.8	14.5	40.3
1990	16.3	12.0	19.1	12.6	22.8	15.5	28.3	117.6	34.2	56.8	61.9	15.9	34.6
1991	7.6	28.2	7.9	8.5	13.5	13.7	17.7	59.1	57.6	42.3	37.5	8.2	25.1
1992	21.5	21.8	10.9	9.5	6.4	14.6	43.1	79.7	35.8	42.7	22.4	61.6	31.0
1993	12.4	7.5	6.6	8.1	21.0	68.0	26.1	13.0	11.0	8.6	24.9	14.9	18.5
1994	13.2	11.8	9.5	19.5	12.3	39.5	56.3	86.3	47.8	45.4	40.2	8.3	32.6
1995	8.5	13.9	15.0	81.9	39.6	45.5	91.8	50.9	49.3	45.5	21.7	43.9	42.4
1996	41.6	25.9	22.5	48.5	70.1	25.1	54.9	50.4	59.8	18.5	8.2	17.0	37.0
1997	17.4	5.6	27.3	11.4	9.1	92.3	40.8	21.3	26.1	43.1	18.8	9.6	27.0
1998	4.3	7.7	14.3	3.3	5.9	43.9	185.5	65.9	49.4	41.4	25.3	19.9	39.3
1999	7.9	3.6	14.3	16.9	24.9	55.3	41.1	44.1	57.9	17.8	82.9	24.0	32.6
2000	9.0	3.5	2.6	16.0	22.6	45.2	33.1	41.6	37.8	28.3	11.8	19.4	22.6
2001	11.8	44.2	12.9	36.1	53.2	23.7	20.6	39.3	36.0	50.0	44.0	89.4	38.4
2002	24.2	13.0	9.7	22.3	15.0	52.4	68.8	34.7	29.5	19.6	12.9	13.9	26.4
2003	8.7	6.5	8.8	8.7	19.0	46.8	38.1	13.2	53.4	88.8	24.3	37.4	29.6
Mean	22.0	17.3	17.0	20.9	23.5	41.0	48.6	47.6	39.9	40.0	32.5	30.6	31.9

Table 27 Whakatane River – Monthly Mean Bed Transport rates (in m^3/s) derived with the Meyer-Peter & Muller equations (7.4 and 7.7)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1981	0.00003	0	0.00012	0.00060	0.00055	0.00128	0.00012	0.00330	0	0.00182	0.01066	0	0.00154
1982	0	0.00260	0.00003	0	0	0.00260	0	0	0	0	0	0	0.00042
1983	0	0	0	0	0	0	0.00385	0.00188	0	0.03211	0.00432	0.01903	0.00518
1984	0	0	0.00022	0.00001	0	0.00001	0.00039	0	0.00001	0	0	0.00743	0.00068
1985	0.00231	0	0	0.00756	0.00121	0.00240	0	0.00187	0.01237	0	0.00007	0.00197	0.00247
1986	0.00733	0	0.00462	0	0.00440	0.00158	0.00164	0.01337	0.00783	0	0	0.00003	0.00344
1987	0.00096	0	0	0.00034	0.00050	0.00016	0	0.00403	0	0	0.00139	0.00553	0.00109
1988	0	0.00022	0.00006	0	0.00013	0	0.00761	0.00252	0.00106	0	0.00561	0.00619	0.00196
1989	0.01543	0.00024	0	0	0.00059	0.00683	0.00462	0	0.00098	0.00709	0.00012	0	0.00303
1990	0	0	0.00002	0.00005	0.00010	0.00100	0	0.02574	0	0.00151	0.00567	0	0.00288
1991	0.00001	0.00293	0	0	0	0	0	0.00671	0.00169	0.00243	0.00028	0	0.00116
1992	0.00051	0.00076	0	0	0	0	0.00489	0.00919	0	0.00060	0	0.00679	0.00192
1993	0	0	0	0.00000	0.00109	0.01020	0	0	0	0	0	0	0.00093
1994	0	0	0	0.00005	0	0.00310	0.01744	0.01213	0.00278	0.00017	0.00120	0	0.00311
1995	0.00014	0	0.00000	0.01429	0.00136	0	0.01166	0.00532	0.00812	0.00009	0.00000	0.00902	0.00419
1996	0.00417	0	0.00010	0.00102	0.01266	0	0.00153	0.00169	0.00441	0	0	0.00056	0.00220
1997	0	0	0.00009	0	0.00007	0.01640	0	0	0.00067	0.00040	0.00015	0	0.00146
1998	0	0.00000	0.00019	0	0	0.00089	0.06505	0.00490	0.00508	0.00137	0	0.00016	0.00658
1999	0	0	0.00015	0.00011	0	0.00373	0.00116	0.00025	0.00857	0	0.01810	0	0.00264
2000	0	0	0	0.00004	0.00037	0.00406	0.00197	0.00115	0	0.00004	0	0	0.00064
2001	0	0.00823	0	0.00373	0.00368	0	0	0.00001	0.00045	0.00191	0.00001	0.01317	0.00257
2002	0	0	0	0.00368	0	0.00717	0.00269	0	0.00003	0	0	0	0.00112
2003	0	0	0	0.00182	0.00325	0.00117	0.00109	0	0.00089	0.01512	0.00000	0.00090	0.00205
Mean	0.00134	0.00065	0.00024	0.00145	0.00130	0.00272	0.00547	0.00409	0.00239	0.00281	0.00207	0.00308	0.00232

Table 28 Whakatane River – Monthly Mean Bed Transport rates (in m^3/s) derived with the Engelund & Hansen equations (7.5 & 7.8)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1981	0.00008	0	0.00015	0.00032	0.00048	0.00112	0.00052	0.00199	0	0.00099	0.00466	0	0.00086
1982	0	0.00113	0.00012	0	0	0.00124	0.00003	0	0	0	0	0	0.00020
1983	0	0	0	0.00001	0	0	0.00155	0.00081	0	0.01198	0.00253	0.00683	0.00201
1984	0	0	0.00022	0.00005	0	0.00005	0.00032	0	0.00004	0	0	0.00274	0.00029
1985	0.00099	0	0	0.00275	0.00052	0.00130	0.00008	0.00090	0.00459	0	0.00008	0.00126	0.00103
1986	0.00312	0	0.00203	0	0.00193	0.00090	0.00086	0.00530	0.00315	0	0	0.00005	0.00146
1987	0.00049	0	0	0.00034	0.00025	0.00019	0	0.00174	0	0	0.00085	0.00224	0.00051
1988	0	0.00015	0.00006	0	0.00011	0.00004	0.00320	0.00161	0.00070	0	0.00212	0.00244	0.00088
1989	0.00670	0.00034	0	0	0.00031	0.00359	0.00253	0	0.00061	0.00415	0.00009	0	0.00154
1990	0	0	0.00006	0.00008	0.00015	0.00050	0	0.01082	0	0.00115	0.00231	0	0.00127
1991	0.00001	0.00116	0	0	0	0	0	0.00273	0.00114	0.00117	0.00038	0	0.00055
1992	0.00032	0.00041	0	0	0	0	0.00193	0.00463	0	0.00039	0	0.00284	0.00089
1993	0	0	0	0.00001	0.00054	0.00421	0	0	0	0	0	0	0.00039
1994	0	0	0	0.00010	0	0.00156	0.00700	0.00477	0.00150	0.00027	0.00081	0	0.00135
1995	0.00010	0	0.00004	0.00564	0.00070	0	0.00499	0.00214	0.00309	0.00010	0.00006	0.00338	0.00169
1996	0.00173	0	0.00018	0.00082	0.00473	0	0.00104	0.00085	0.00255	0	0	0.00029	0.00102
1997	0	0	0.00023	0.00002	0.00012	0.00671	0	0	0.00038	0.00041	0.00009	0	0.00066
1998	0	0.00001	0.00013	0	0	0.00077	0.02321	0.00246	0.00211	0.00085	0	0.00013	0.00251
1999	0	0	0.00018	0.00013	0	0.00215	0.00061	0.00024	0.00345	0	0.00690	0	0.00113
2000	0	0	0	0.00004	0.00027	0.00230	0.00093	0.00069	0	0.00006	0	0	0.00036
2001	0	0.00312	0	0.00151	0.00173	0	0	0.00003	0.00031	0.00115	0.00002	0.00636	0.00118
2002	0	0	0	0.00141	0	0.00314	0.00233	0	0.00007	0	0	0	0.00058
2003	0	0	0	0.00072	0.00129	0.00088	0.00073	0	0.00059	0.00649	0.00004	0.00070	0.00097
Mean	0.00059	0.00027	0.00015	0.00061	0.00057	0.00133	0.00225	0.00181	0.00105	0.00127	0.00091	0.00127	0.00101

Table 29 Whakatane River – Monthly Mean Bed Transport rates (in m^3/s) derived with the Einstein & Brown equations (7.6 & 7.9)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1981	0.00002	0	0.00006	0.00022	0.00023	0.00055	0.00014	0.00123	0	0.00066	0.00374	0	0.00057
1982	0	0.00090	0.00003	0	0	0.00092	0.00001	0	0	0	0	0	0.00015
1983	0	0	0	0.00000	0	0	0.00133	0.00065	0	0.01227	0.00160	0.00688	0.00193
1984	0	0	0.00010	0.00002	0	0.00001	0.00016	0	0.00001	0	0	0.00260	0.00025
1985	0.00082	0	0	0.00267	0.00042	0.00087	0.00001	0.00066	0.00442	0	0.00003	0.00075	0.00088
1986	0.00255	0	0.00163	0	0.00155	0.00058	0.00059	0.00465	0.00271	0	0	0.00002	0.00120
1987	0.00034	0	0	0.00015	0.00018	0.00008	0	0.00139	0	0	0.00052	0.00192	0.00039
1988	0	0.00009	0.00003	0	0.00005	0.00001	0.00269	0.00097	0.00040	0	0.00193	0.00218	0.00070
1989	0.00540	0.00013	0	0	0.00021	0.00247	0.00167	0	0.00037	0.00263	0.00005	0	0.00109
1990	0	0	0.00002	0.00003	0.00006	0.00035	0	0.00920	0	0.00061	0.00196	0	0.00103
1991	0.00000	0.00099	0	0	0	0	0	0.00231	0.00065	0.00085	0.00015	0	0.00041
1992	0.00019	0.00028	0	0	0	0	0.00170	0.00326	0	0.00023	0	0.00238	0.00068
1993	0	0	0	0.00000	0.00039	0.00350	0	0	0	0	0	0	0.00032
1994	0	0	0	0.00003	0	0.00114	0.00646	0.00433	0.00100	0.00010	0.00046	0	0.00114
1995	0.00005	0	0.00001	0.00506	0.00049	0	0.00403	0.00185	0.00288	0.00004	0.00001	0.00325	0.00148
1996	0.00146	0	0.00006	0.00042	0.00451	0	0.00059	0.00060	0.00162	0	0	0.00020	0.00080
1997	0	0	0.00007	0.00000	0.00004	0.00585	0	0	0.00024	0.00018	0.00006	0	0.00053
1998	0	0.00000	0.00007	0	0	0.00038	0.02642	0.00177	0.00176	0.00052	0	0.00007	0.00263
1999	0	0	0.00007	0.00005	0	0.00137	0.00042	0.00011	0.00301	0	0.00657	0	0.00096
2000	0	0	0	0.00002	0.00015	0.00149	0.00070	0.00043	0	0.00002	0	0	0.00023
2001	0	0.00286	0	0.00129	0.00131	0	0	0.00001	0.00017	0.00072	0.00001	0.00468	0.00091
2002	0	0	0	0.00128	0	0.00256	0.00114	0	0.00002	0	0	0	0.00041
2003	0	0	0	0.00064	0.00113	0.00047	0.00042	0	0.00034	0.00533	0.00001	0.00037	0.00074
Mean	0.00047	0.00023	0.00009	0.00052	0.00047	0.00098	0.00211	0.00145	0.00085	0.00105	0.00074	0.00110	0.00084

Estimated annual averages of material transported (Table 30) are obtained by multiplying the mean annual transport rates derived in Tables 27 to 29 by the seconds in a year.

Table 30 Whakatane River – Sediment Transport – Calculated Annual Average

Methods	**Transport Rates (m^3/year)**
MEYER-PETER & MULLER	73,000
ENGELUND & HANSEN	32,000
EINSTEIN & BROWN	26,500
Average	43,833

The monthly mean data show how episodic the movement of gravel material is, with large amounts moved during short flood events, and little movement over extended periods of low to medium flows. There are large variations in the calculated transport capacity of the river with the three sets of equations. The ratings based on the Meyer-Peter & Muller transport rates give the largest total transport annual rate, with almost three times the rate of the Einstein & Brown formulae and over two times the rate of the Engelund & Hansen formulae (Table 30).

In an earlier study of the Whakatane River, Eynon-Richards (1988) estimates of the bed load transport at the Valley Road gauging station using the Meyer-Peter & Muller and the Einstein-Brown method are 139.5kt/year and 84.5kt/year respectively. Those values converted to cubic metre using the volume conversion of 1600kg/m^3 give 87,188

m^3/year and 52,813 m^3/year respectively (Table 30A). Also, cited in Eynon-Richards (1988) are the estimates at Valley Road gauging station by Freestone in 1977 and Adams in 1982 of the bedload volumes of 109,375 m^3/year and 33,125 m^3/year respectively. Note that Adams used the Einstein-Brown method whereas Freestone used the Meyer-Peter & Muller method. These earlier studies confirm that the Meyer-Peter & Muller formula results in significantly higher sediment transport rates than the Einstein & Brown formula, as our analysis has shown.

Table 30A Bed load transport from previous studies at Valley Road gauging station

Study	Meyer-Peter & Muller m^3/s	Einstein & Brown m^3/s
Eynon-Richards (1988)	87,188	52,813
Adams (1982)	-	33,125
Freestone (1977)	109,375	-

7.7 Total Bed Transport in the Whirinaki River

Estimates of the amount of bed material transported down the Whirinaki River were obtained by applying the transport rating curves (Equations 7.10, 7.11, 7.12 (Figure 23) and Equations 7.13, 7.14, and 7.15 (Figures 24)) to the available continuous flow records, where flows were generated by applying flow rating curves to instantaneous water level records at the recorder site. The monthly mean flows are shown in Table 31 and the monthly means of the calculated continuous transport rates are given in Tables 32 to 34. Zero transport was assumed for any flow less than 25m^3/s. In order to have continuous monthly mean flows any gaps in the time series have been deleted where the flow is below the sediment threshold of 25m^3/s. Into any gaps which are above this threshold synthetic data has been inserted where possible. In the tables, the "?" represents months with missing flow data where no reliable synthetic data was available.

The annual averages of material transport rates over the recorded years are calculated for the three formulae by multiplying the mean annual transport rates derived in Tables 32 to 34 by the seconds in a year and the results are shown in Table 35.

Table 31 Mean monthly flow (in m³/s) of the Whirinaki River

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
1970	8.0	4.9	5.3	6.4	6.9	24.1	?	?	36.5	36.0	26.2	10.7	16.5
1971	11.0	10.9	11.1	8.4	28.4	31.3	11.4	14.3	32.0	32.6	20.5	22.1	19.5
1972	13.1	6.7	21.8	8.8	8.1	7.6	20.8	14.7	13.1	14.1	8.4	6.0	12.0
1973	6.9	4.5	5.9	5.0	7.3	14.6	7.3	16.2	22.8	14.9	10.8	7.8	10.3
1974	5.6	5.2	4.5	16.6	12.2	20.2	34.4	26.8	16.9	20.7	14.5	20.5	16.6
1975	14.9	9.2	9.1	8.9	13.4	31.0	16.7	17.9	21.6	24.0	15.6	8.8	15.9
1976	26.0	30.3	9.4	9.2	13.7	13.8	14.7	18.9	18.9	18.3	14.4	11.6	16.5
1977	8.8	9.1	6.0	5.6	9.3	20.6	22.5	17.4	13.4	11.3	7.7	9.9	11.8
1978	6.5	4.9	3.7	6.6	5.1	5.9	21.6	11.9	13.0	12.5	19.6	13.3	10.4
1979	8.2	10.6	21.4	14.7	19.0	10.9	10.3	27.1	28.3	27.3	21.1	13.4	17.7
1980	19.6	10.7	8.2	14.9	10.7	12.1	19.2	19.6	22.0	11.0	11.7	21.3	15.1
1981	13.3	9.6	7.8	8.8	12.7	21.9	26.3	25.7	13.8	14.5	17.7	17.7	15.9
1982	14.6	8.3	8.5	9.9	10.8	15.2	10.4	10.2	8.4	7.9	6.8	8.5	10.0
1983	7.0	4.5	3.7	5.8	7.6	10.6	13.4	10.9	14.3	38.0	28.2	12.8	13.1
1984	7.9	11.4	17.8	11.5	7.8	9.9	18.2	14.8	15.6	11.3	7.1	18.4	12.7
1985	14.8	9.8	8.3	10.7	8.1	14.5	17.4	17.4	19.1	9.3	8.5	16.6	12.9
1986	34.3	12.9	12.8	8.1	11.4	16.4	17.9	25.0	22.2	15.0	11.2	7.1	16.2
1987	10.7	7.0	7.6	10.0	9.1	14.0	10.2	15.7	9.3	10.9	10.7	15.3	10.9
1988	9.0	6.2	10.3	5.3	8.1	16.4	24.9	28.1	29.7	25.5	12.8	18.0	16.2
1989	34.6	17.2	9.4	6.3	11.0	27.7	24.6	10.9	12.8	29.9	15.6	9.1	17.4
1990	9.2	8.4	14.1	9.9	16.8	13.0	14.0	31.9	15.2	30.2	28.2	12.5	17.0
1991	7.1	11.5	7.6	8.0	10.6	9.8	12.7	30.5	19.2	16.7	16.8	7.9	13.2
1992	10.2	12.2	8.4	7.2	5.6	8.2	15.6	31.8	19.9	17.8	11.7	26.3	14.6
1993	10.6	6.5	5.2	7.1	8.6	26.4	13.1	6.8	5.9	5.0	9.1	8.1	9.4
1994	6.9	5.8	4.7	8.3	9.1	24.8	28.4	33.0	18.5	21.8	22.7	9.7	16.2
1995	7.1	8.8	7.8	21.3	16.1	17.9	32.9	21.8	23.0	25.1	16.1	22.6	18.4
1996	14.2	12.1	12.9	25.1	25.5	15.9	21.6	19.8	26.0	12.0	8.9	11.6	17.1
1997	9.9	6.9	12.0	12.2	9.2	32.9	19.7	12.4	12.4	17.0	11.6	7.5	13.7
1998	5.2	6.5	7.2	7.4	8.0	19.3	69.2	29.7	22.7	22.9	16.5	9.2	18.8
1999	7.1	5.0	5.7	7.3	11.1	21.6	17.5	21.4	20.3	10.4	22.5	13.5	13.7
2000	9.0	6.1	4.3	6.5	7.9	19.8	14.7	14.9	16.3	18.7	8.4	10.2	11.4
2001	10.2	11.5	9.5	11.3	15.3	12.4	10.7	19.3	14.4	14.0	25.5	33.0	15.6
2002	16.6	10.4	7.5	8.4	10.7	22.3	29.9	15.5	13.5	12.5	7.8	12.7	14.0
2003	6.8	4.4	4.7	4.6	6.6	14.9	12.2	7.6	23.9	30.5	16.3	28.7	13.5
Mean	11.9	9.1	8.9	9.6	11.2	17.6	19.8	19.4	18.7	18.8	15.0	14.2	14.5

Table 32 Whirinaki River – Monthly Mean Bed Transport rates (in m^3/s) derived with the Meyer-Peter & Muller equations (7.10 and 7.13)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
1970	0	0	0	0	0	0.0069	?	?	0.01511	0.01854	0.00708	0	0.00476
1971	0	0.0005	0.00017	0.00015	0.01445	0.01197	0	0.00016	0.00922	0.0106	0.00118	0.00407	0.00439
1972	0.00039	0	0.0063	0	0	0	0.00256	0.0001	0	0.00097	0	0	0.00087
1973	0.00012	0	0	0	0	0.00063	0	0.00209	0.00603	0.0002	0.00007	0	0.00076
1974	0	0	0	0.00621	0.00001	0.00285	0.01338	0.00398	0.00031	0.0013	0	0.00122	0.00246
1975	0.00001	0	0.00006	0	0.00004	0.00913	0.00001	0.00325	0.00328	0.00638	0.0002	0.00008	0.00187
1976	0.00637	0.01419	0.00002	0.00066	0.00117	0.00004	0.00016	0.00042	0.00141	0.00002	0	0	0.00199
1977	0	0.00041	0.00001	0	0.00033	0.00327	0.00379	0.00008	0	0	0	0.00002	0.00066
1978	0	0	0	0.00013	0	0	0.00531	0	0.00008	0	0.00618	0.00001	0.00098
1979	0	0.00117	0.00499	0.00012	0.002	0	0.00006	0.00544	0.00676	0.0068	0.00183	0	0.00244
1980	0.00232	0	0	0.00058	0	0.00003	0.00049	0.00186	0.00093	0	0	0.00458	0.00091
1981	0.00008	0	0	0	0.00115	0.00138	0.00568	0.00408	0	0.00014	0.00114	0.00053	0.0012
1982	0.00099	0.00018	0	0.00006	0	0.00075	0	0	0	0	0	0.00002	0.00017
1983	0	0	0	0	0	0	0.00086	0.00014	0	0.02031	0.00897	0.00012	0.00256
1984	0	0.00048	0.00052	0.00018	0	0.00003	0.00009	0	0.00018	0	0	0.00438	0.00049
1985	0	0	0.00003	0.00229	0	0.00044	0.00196	0.00129	0.00183	0	0	0.0008	0.00072
1986	0.01725	0	0.00066	0.00001	0.00021	0.00018	0.00229	0.00555	0.00314	0	0	0	0.00248
1987	0.00111	0	0	0.00036	0.00014	0.00016	0	0.00227	0	0.00001	0	0.00195	0.00051
1988	0	0	0.00016	0	0.00015	0.00137	0.01267	0.0052	0.01012	0.00462	0.00002	0.00345	0.00317
1989	0.01351	0.00066	0	0	0.00149	0.00846	0.00358	0	0.00015	0.0081	0.00009	0	0.00303
1990	0	0	0.00038	0.00006	0.00214	0.0001	0	0.01063	0	0.00935	0.00594	0	0.00241
1991	0	0.0004	0	0	0.00001	0.00001	0.00028	0.0109	0.00074	0.00008	0.00087	0.00004	0.00112
1992	0.00014	0.00092	0	0.00006	0	0	0.00051	0.01131	0.00056	0.00022	0	0.00607	0.00167
1993	0	0	0	0.00001	0.00025	0.00778	0	0	0	0	0.00013	0	0.00067
1994	0	0	0	0.00031	0	0.00655	0.00759	0.01198	0.00136	0.0013	0.00524	0	0.00288
1995	0	0	0	0.00234	0.00046	0.00006	0.0107	0.00271	0.00483	0.00329	0.00005	0.00672	0.00263
1996	0.00009	0.00001	0.00044	0.00503	0.00681	0	0.00166	0.00085	0.00502	0	0	0.00002	0.00166
1997	0	0	0.00014	0.00074	0.00015	0.0118	0.00085	0	0.00013	0.00018	0.00023	0	0.00117
1998	0	0.00001	0	0	0	0.00173	0.05744	0.00685	0.00228	0.00245	0.00013	0	0.00601
1999	0	0	0	0.00007	0.00021	0.00289	0.00016	0.0007	0.00116	0	0.00547	0.00003	0.00088
2000	0	0	0	0	0	0.00522	0.00032	0	0.00009	0.00186	0	0.00004	0.00062
2001	0	0.00081	0	0.00027	0.00024	0	0	0.00111	0	0.00005	0.00294	0.01246	0.0015
2002	0.00031	0.00004	0	0.00075	0.00003	0.00519	0.00892	0	0.00014	0	0	0.00028	0.00131
2003	0	0	0	0.00003	0.00031	0.00043	0	0	0.00291	0.01002	0.00263	0.0086	0.0021
Mean	0.00126	0.00058	0.00041	0.00060	0.00093	0.00263	0.00428	0.00282	0.00229	0.00314	0.00148	0.00163	0.00185

Table 33 Whirinaki River – Monthly Mean Bed Transport rates (in m^3/s) derived with the Engelund & Hansen Equations (7.11 and 7.14)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
1970	0	0	0	0	0	0.00221	?	?	0.00562	0.0054	0.00261	0	0.00158
1971	0	0.00021	0.00009	0.00007	0.00401	0.00383	0	0.00021	0.00457	0.00445	0.00103	0.00167	0.00168
1972	0.00028	0	0.00212	0	0	0	0.00151	0.00008	0	0.00041	0	0	0.00037
1973	0.00005	0	0	0	0	0.00044	0	0.00094	0.00238	0.00025	0.00005	0	0.00034
1974	0	0	0	0.0018	0.00003	0.00111	0.00503	0.00251	0.00017	0.00097	0	0.00086	0.00105
1975	0.00003	0	0.00004	0	0.00003	0.00379	0.00003	0.00097	0.00139	0.0025	0.00012	0.00006	0.00075
1976	0.00254	0.00388	0.00004	0.00021	0.00047	0.00004	0.0001	0.00045	0.00082	0.00005	0	0	0.00071
1977	0	0.00021	0.00001	0	0.00014	0.00128	0.00163	0.00013	0	0	0	0.00005	0.00029
1978	0	0	0	0.00012	0	0	0.00179	0	0.00009	0	0.00179	0.00003	0.00032
1979	0	0.00043	0.00203	0.00007	0.00096	0	0.00008	0.00268	0.00303	0.00283	0.00107	0	0.00111
1980	0.00094	0	0	0.00037	0	0.00003	0.00034	0.00084	0.00099	0	0	0.00165	0.00043
1981	0.0001	0	0	0	0.00046	0.00114	0.00238	0.00229	0	0.00014	0.00058	0.00039	0.00063
1982	0.00044	0.00009	0	0.00008	0	0.00034	0	0	0	0	0	0.00002	0.00008
1983	0	0	0	0	0	0	0.0004	0.00009	0	0.0058	0.00352	0.00009	0.00083
1984	0	0.00025	0.00043	0.00009	0	0.00004	0.00017	0	0.00014	0	0	0.00142	0.00021
1985	0.00001	0	0.00004	0.00066	0	0.00037	0.00079	0.00055	0.00097	0	0	0.00039	0.00032
1986	0.00471	0	0.00026	0.00002	0.0002	0.00017	0.00094	0.00205	0.00127	0	0	0	0.00081
1987	0.00049	0	0	0.00016	0.0001	0.00015	0	0.00082	0	0.00003	0	0.00079	0.00021
1988	0	0	0.00015	0	0.00008	0.00069	0.00327	0.00297	0.00347	0.00233	0.00003	0.00112	0.00118
1989	0.00485	0.00062	0	0	0.00063	0.00324	0.00209	0	0.00011	0.00354	0.00011	0	0.00128
1990	0	0	0.00035	0.00004	0.0009	0.00007	0	0.00416	0	0.0037	0.00333	0	0.00105
1991	0	0.00022	0	0	0.00002	0.00002	0.00034	0.00363	0.00079	0.00011	0.00051	0.00002	0.00048
1992	0.00007	0.00037	0	0.00004	0	0	0.00032	0.00434	0.00065	0.00017	0	0.00258	0.00072
1993	0	0	0	0.00002	0.00012	0.00268	0	0	0	0	0.00008	0	0.00024
1994	0	0	0	0.00016	0	0.00249	0.00311	0.00442	0.00063	0.00091	0.00171	0	0.00113
1995	0	0	0	0.0012	0.00036	0.0001	0.00447	0.00119	0.00173	0.00216	0.00007	0.00216	0.00113
1996	0.00008	0.00002	0.00022	0.00198	0.00243	0	0.00112	0.00056	0.0026	0	0	0.00003	0.00075
1997	0	0	0.00014	0.00028	0.00009	0.00422	0.00066	0	0.00014	0.00022	0.00012	0	0.00049
1998	0	0.00002	0	0	0	0.00121	0.01492	0.00358	0.00113	0.00181	0.00026	0	0.00194
1999	0	0	0	0.00004	0.00015	0.00135	0.00018	0.00067	0.00094	0	0.00178	0.00003	0.00042
2000	0	0	0	0	0	0.00177	0.00035	0	0.00013	0.00085	0	0.00004	0.00026
2001	0	0.00032	0	0.00015	0.00015	0	0	0.00109	0	0.00008	0.00215	0.00424	0.00069
2002	0.00013	0.00004	0	0.00027	0.00004	0.00214	0.00321	0	0.00011	0	0	0.00017	0.00051
2003	0	0	0	0.00003	0.00015	0.00039	0.00001	0	0.00203	0.00388	0.00095	0.00306	0.00088
Mean	0.00043	0.00020	0.00017	0.00023	0.00034	0.00104	0.00149	0.00125	0.00106	0.00125	0.00064	0.00061	0.00073

Table 34 Whirinaki River – Monthly Mean Bed Transport rates (in m^3/s) derived with the Einstein & Brown Equations (7.12 & 7.15)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	MEAN
1970	0	0	0	0	0	0.00276	?	?	0.00664	0.00724	0.00307	0	0.00197
1971	0	0.00024	0.0001	0.00008	0.00549	0.00473	0	0.00021	0.00501	0.00512	0.00106	0.00191	0.002
1972	0.00029	0	0.00257	0	0	0	0.00161	0.00008	0	0.00047	0	0	0.00042
1973	0.00006	0	0	0	0	0.00046	0	0.00105	0.00275	0.00025	0.00005	0	0.00038
1974	0	0	0	0.00236	0.00003	0.0013	0.00587	0.00266	0.00018	0.00101	0	0.00091	0.0012
1975	0.00003	0	0.00005	0	0.00004	0.00433	0.00002	0.00121	0.00157	0.0029	0.00013	0.00006	0.00086
1976	0.00291	0.00558	0.00004	0.00026	0.00055	0.00004	0.00011	0.00045	0.00088	0.00005	0	0	0.00089
1977	0	0.00023	0.00001	0	0.00015	0.00149	0.00184	0.00013	0	0	0	0.00004	0.00032
1978	0	0	0	0.00012	0	0	0.00218	0	0.00009	0	0.00238	0.00003	0.0004
1979	0	0.0005	0.00233	0.00008	0.00106	0	0.00008	0.00295	0.00339	0.00327	0.00114	0	0.00124
1980	0.00107	0	0	0.00039	0	0.00003	0.00036	0.00094	0.001	0	0	0.00194	0.00048
1981	0.0001	0	0	0	0.00053	0.00117	0.0027	0.00246	0	0.00014	0.00063	0.0004	0.00069
1982	0.0005	0.0001	0	0.00008	0	0.00038	0	0	0	0	0	0.00002	0.00009
1983	0	0	0	0	0	0	0.00044	0.00009	0	0.00793	0.00406	0.00009	0.00106
1984	0	0.00027	0.00044	0.0001	0	0.00004	0.00017	0	0.00014	0	0	0.00176	0.00025
1985	0.00001	0	0.00004	0.00089	0	0.00038	0.00091	0.00063	0.00105	0	0	0.00043	0.00036
1986	0.00666	0	0.0003	0.00002	0.0002	0.00018	0.00108	0.00242	0.00146	0	0	0	0.00104
1987	0.00056	0	0	0.00018	0.0001	0.00015	0	0.00098	0	0.00003	0	0.00092	0.00025
1988	0	0	0.00015	0	0.00009	0.00076	0.00459	0.0032	0.00421	0.00256	0.00002	0.00142	0.00143
1989	0.00579	0.00063	0	0	0.00073	0.00378	0.00223	0	0.00011	0.004	0.00011	0	0.00146
1990	0	0	0.00035	0.00004	0.00102	0.00007	0	0.00485	0	0.00426	0.0036	0	0.0012
1991	0	0.00024	0	0	0.00002	0.00002	0.00034	0.00463	0.0008	0.00011	0.00054	0.00003	0.00057
1992	0.00008	0.00043	0	0.00004	0	0	0.00034	0.00502	0.00065	0.00017	0	0.00293	0.00081
1993	0	0	0	0.00002	0.00013	0.00328	0	0	0	0	0.00009	0	0.00029
1994	0	0	0	0.00017	0	0.00293	0.00357	0.00519	0.0007	0.00095	0.00217	0	0.00131
1995	0	0	0	0.0013	0.00037	0.0001	0.00512	0.00134	0.0021	0.00227	0.00007	0.00276	0.0013
1996	0.00008	0.00002	0.00024	0.0023	0.00292	0	0.00117	0.00059	0.00283	0	0	0.00003	0.00085
1997	0	0	0.00014	0.00033	0.00009	0.00513	0.00068	0	0.00014	0.00022	0.00013	0	0.00057
1998	0	0.00002	0	0	0	0.00126	0.0223	0.00389	0.00125	0.00188	0.00025	0	0.00261
1999	0	0	0	0.00004	0.00015	0.00149	0.00018	0.00068	0.00096	0	0.00227	0.00003	0.00048
2000	0	0	0	0	0	0.00214	0.00036	0	0.00013	0.00096	0	0.00004	0.0003
2001	0	0.00037	0	0.00016	0.00016	0	0	0.00111	0	0.00008	0.00224	0.00517	0.00078
2002	0.00015	0.00004	0	0.00032	0.00004	0.00248	0.00383	0	0.00011	0	0	0.00018	0.0006
2003	0	0	0	0.00003	0.00017	0.00039	0.00001	0	0.00213	0.00447	0.00111	0.00373	0.00101
Mean	0.00054	0.00026	0.00020	0.00027	0.00041	0.00121	0.00188	0.00142	0.00118	0.00148	0.00074	0.00073	0.00087

Table 35 Whirinaki River – Sediment Transport – Calculated Annual Average

METHODS	TRANSPORT RATES (m^3/year)
MEYER-PETER & MULLER	58,500
ENGELUND & HANSEN	23,100
EINSTEIN & BROWN	27,300
Average	36,300

There are large variations in the calculated transport capacities of the river using the three methods. The Meyer-Peter & Muller method gives by far the highest transport capacity, being more than twice as high than that derived with the Einstein & Brown method and two a half times higher than that derived with the Engelund & Hansen method.

The Engelund & Hansen method is more applicable to channels possessing a duned bed, which is a likely characteristic of the lower Whirinaki River bed. The Einstein and Brown method is more applicable to high flood flows and will tend to underestimate bed load transport for low to extreme low flow.

With the Meyer-Peter and Muller method, discrepancies between the observed and estimated bedload transport rates can occur when the energy gradient exceeds 0.001. The design energy gradient of the Whirinaki River is greater than 0.001. However, the Whirinaki River is a shallow gravel bed river with the design 1% AEP flood event water depth between 2.4 and 4.3 metres.

Chapter 8: Transport Balance

The inflow of gravel from the upper reach of a river can be derived from the difference between the net volumetric change of bed levels and gravel extraction quantities. The volumetric change in riverbed levels is estimated from inter-survey bed level changes. Thus, using the cross-section geometry and the profile distance between selected cross-sections, inter-survey volume changes can be calculated (see Tables 36). The volumetric changes include both coarse and fine sediments over the entire width of the cross-sections. A previous Whakatane River study (Titchmarsh, 1992) showed a percentage of less than 20 by weight of sand to coarser sediment. This trend is also observed for the Whirinaki River (see Figures 5 and 6). The precise influence this has on the transport balance is uncertain.

8.1 Whakatane River

Table 37 shows details of gravel extraction in the middle reach of the Whakatane River in the years 1993 to 1998. Extracted gravel data upstream of the confluence of the Whakatane and Waimana rivers are available only from 1996 (see Table 38). The information is taken from the operators' quarterly returns. The records are given in terms of gravel sold or after it has been screened and processed. The sediment extracted is usually coarse and fine sediment. For river management and net transport balance purposes the relevant measure is the quantity removed from the river, not just the commercial components of the gravel removed. However, in the absence of the quantity removed the transport balance has to be estimated with the available data. The results will thus be an approximation only. Extraction has taken place since 1963, with an average annual extraction since 1979 of 75,000m^3/year upstream of the Pekatahi Bridge. Since 1996, a considerable portion of extraction has been from outside the active channel to allow bed levels to aggrade in some places.

From Table 38 it is evident that while gravel extraction above the Whakatane/Waimana confluence has taken place, there was an increase in volume over the same time period above the confluence. On the other hand, gravel extraction above Pekatahi Bridge for the years 1994-1996 and 1996-1998 is much higher than the bed volume change above Pekatahi Bridge. The years 1996 to 1998 comparisons give an estimated annual supply above the Whakatane/Waimana confluence (42,225m^3) close to the average of the three bed material transport rates (Chapter 7) using the derived equations (43,833m^3). The large volumetric change in bed level over the 1998 year is due mainly to the flood of July of the same year when a large amount of sediment from the river catchment was undoubtedly added to the riverbed volume change. It is possible that the real extraction figure of the years 1994 to 1997 is larger than that suggested in Table 36 and that the river has degraded during that period due to over mining. This is reflected by the sediment deficit over the years 1994 to 1996.

Table 36 Whakatane River – Estimated channel bed volume (in m^3) changes between cross-sections

Cross-section	Period					
	1965 – 1977	1977 – 1991	1991 – 1994	1994 – 1996	1996 – 1998	Apr-Dec 1998
31 - 30	-	-3965	13183	-9218	8700	54787
32 – 31	-	-2971	880	2091	4200	15694
33 – 32	-	-27400	9418	17982	2800	43716
34 – 33	2199	-100004	-1513	3067	1200	29441
35 – 34	-42046	-59760	-14776	7222	6400	1727
36 – 35	-14304	-24959	-5331	-1018	2600	5226
37 – 36	-23219	-62589	-4167	-2471	3600	24949
38 – 37	-26334	-30275	-4922	13579	1300	10345
39 – 38	-6621	-27796	-1194	-2407	-5100	-23361
40 – 39	-14699	-62798	-15263	-16312	-3100	-2413
41 – 40	-13783	-43361	-15103	-2936	2300	-31155
42 – 41	-44506	-17110	-10761	-18038	12800	-79648
43 – 42	-27743	-39279	-10874	-14715	8200	213
44 – 43	-28721	-29447	-5055	-1967	-6800	17504
45 – 44	-104745	-37468	-4433	-4063	-6100	52513
46 – 45	-61929	-17836	-3740	-2178	7600	16006
47 – 46	-17095	-12935	-1807	5926	9600	-6788
48 – 47	-19610	-21196	-16419	3533	10300	19864
49 – 48	-76608	-	-11707	-16619	-8900	18336
50 – 49	-	14946	-18985	4039	-2100	-16704
51 – 50	-	27777	-24039	-3738	10000	18380
52 – 51	-160668	2732	14001	-19034	-6700	68815
53 – 52	-	-44783	21509	23274	-5000	27872
54 – 53	-89400	-84145	5833	3479	200	11806
55 – 54	-88880	-158755	30509	4509	300	111556
56 – 55	-	-11768	5724	6044	-500	92435
57 – 56	-42970	-65251	-6424	-11449	-1600	66983
58 – 57	-53580	-7158	1716	3864	10800	75503
Total (m^3)	**-955262**	**-947554**	**-73740**	**-27554**	**52000**	**623602**
Average (m^3)	-79605	-78963	-6145	-2296	4333	22272

Note: positive value means aggradation whilst negative value means degradation.

Table 37 Whakatane River – Recorded Gravel Extraction

YEAR	EXTRACTION (m^3)	
	Above confluence with Waimana River	Upstream of Pekatahi Bridge
1993	-	32601
1994	-	62074
1995	-	56247
1996	15650	62583
1997	16800	59407
1998	39718	39718

Table 38 Whakatane River – Transport Balance in m³

Year	Gravel extraction		Volume change		Net supply		Annual net supply	
	Above confluence with Waimana River	Upstream of Pekatahi Bridge	Above confluence with Waimana River	Upstream of Pekatahi Bridge	Above confluence with Waimana River	Upstream of Pekatahi Bridge	Above confluence with Waimana River	Upstream of Pekatahi Bridge
1994 - 1996	-	118,321	-27,554	-16,922	-	101,399	-	50,699
1996 - 1998	32,450	121,990	52,000	57,100	84,450	179,090	42,225	89,545
1998 - 1999	39,718	39,718	623,602	825,584	663,320	865,302	663,320	865,302

It is impossible to make a clear comparison between the figures derived from the bed material transport analysis in Chapter 7 and the volumetric changes in the bed due to the lack of accurate data on sediment extraction and the percentage of the volume representing the throughput material, the throughput material being the sediment found on the stream bed surface discontinuously (in space and time) and which is finer than the bulk of the river bed sediment. This comparison can be made when adequate data are collected through the years to come. The 1995/96 Natural Environment Regional Monitoring Network River and Stream Channel Monitoring Programme Report (Surman, 1997) estimated that the annual bedload transport rate is in the range of 40,000m^3/year. This value is fairly close to the average of the estimates derived using the Engelund & Hansen, Einstein & Brown and Meyer-Peter & Muller methods (Table 30).

In face of the lack of good reason to favour one of the three formulae over the others, it is concluded that the average of the three methods is the best estimator of bed load in the middle Whakatane River reach, with 44,000m^3/year.

8.2 Whirinaki River

Table 39 and Figures 25 to 32 show the bed volume and reduced level changes over the years 1994 to 1999. The Figures show lateral erosion (at cross-sections 2 and 5) as well as sediment build-up (especially at cross-section 4) in the channel. At cross-section 5 the thalweg of the bed has shifted from the true right to the true left.

Table 39 Whirinaki River – Estimated channel bed volume and area changes

Cross-section	**Distance (km)**	**Volume Change (m³)**	
		Periods	
		1994 – 1997	***1997 - 1999***
1 - Whirinaki	0.57	0	0
2 – 1	1.52	1,079	-1184
3 – 2	2.16	915	-2802
4 – 3	3.16	19,224	12365
5 – 4	4.57	26,933	19222
6 – 5	5.87	2,687	1015
7 – 6	6.665	-17,049	21189
8 – 7	7.21	-11,956	10119
	Total	21,833	59,924
	Average	4,328	29,962

Table 40 Whirinaki River – Observed Sediment Transport Balance (in m^3)

Years	Gravel Extraction	Channel Volume Change	Net Supply	Annual Net Supply
1994-1997	50,018	17,312	67,330	22,443
1997-1999	0	59,924	59,924	29,962

Table 41 Whirinaki River – Sediment Transport Rates – Annual Average

Methods	Transport rates (m^3/year)	
	1994 - 1996	1997 - 1999
MEYER-PETER & MULLER	75,371	84,727
ENGELUND & HANSEN	31,641	29,959
EINSTEIN & BROWN	36,372	38,474
Average	*47,794*	*51,053*

Bed volume changes were analysed using surveyed bed cross-section data collected over the period 1994 to 1999. The analysis shows that over two separate periods 1994 to 1997 and 1997 to 1999 the average annual bed load supplies are approximately 22,500m^3/s and 30,000m^3/s respectively (Table 40). Note that those bed volume changes are composed of coarse and fine material. The fine material accounts for approximately 20% by weight of the total bed material (See Chapter 4 and Figures 5 to 7).

The mean annual sediment transport rates from the three formulae derived in Chapter 7 for the years 1994 to 1999 (Tables 32 - 34) were used to estimate the average annual bed material transport rate over the period 1994 to 1999 (Table 41). The observed annual sediment load over the period 1994 to 1999 (Table 40) fits best to the estimate derived by the Engelund & Hansen method. Both the Einstein & Brown and particularly the Meyer-Peter & Muller methods seem to over-estimate the sediment transport rates.

An absolute comparison of observed volume changes and estimated sediment transport rates is not possible. However, based on the results obtained for the period 1994 to 1999, it can be deducted that the Engelund & Hansen method is the best suited estimator of sediment load transport for the Lower Whirinaki River. It estimates that the annual bed load transport for the Lower Whirinaki River is 23,000m^3/year (Table 35).

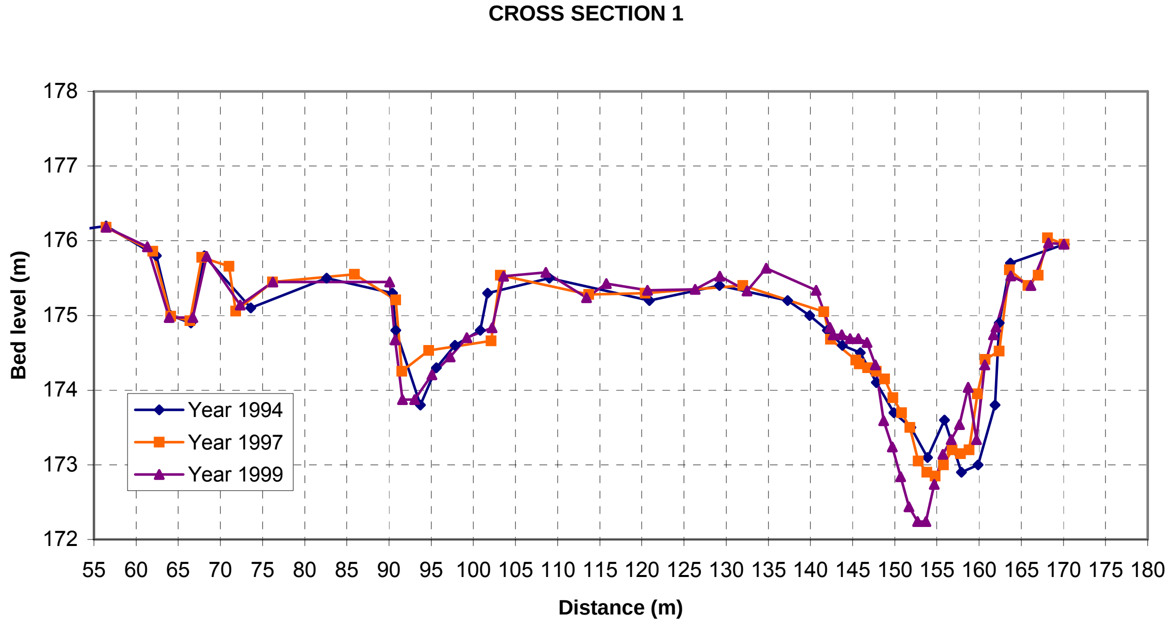

Figure 25 Whirinaki River – Reduced bed level at cross section 1

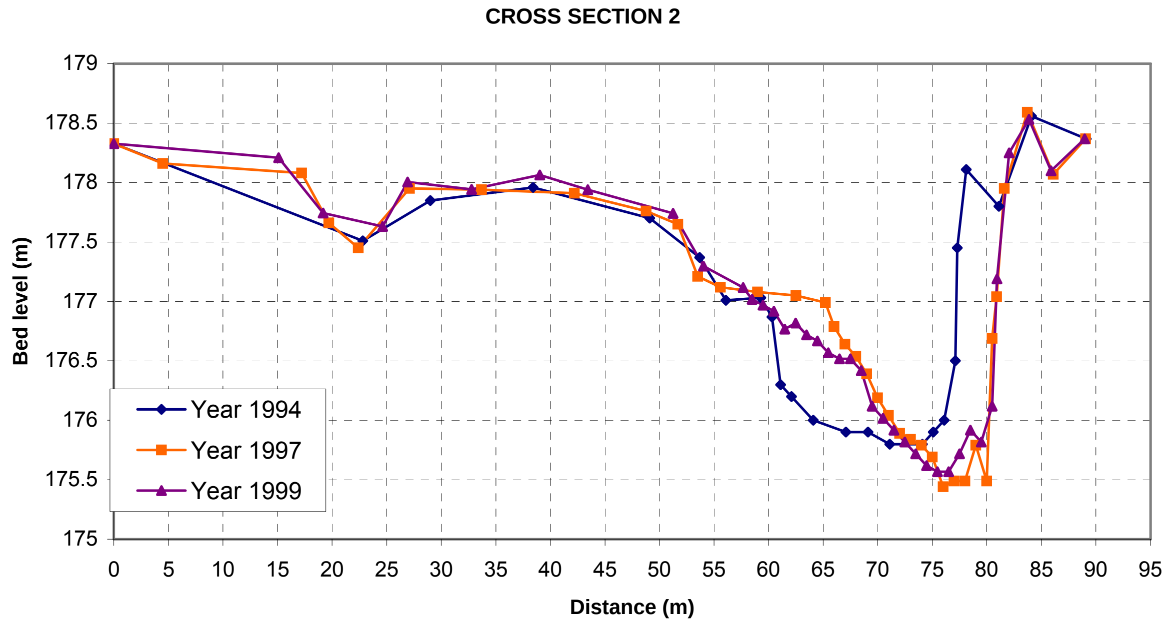

Figure 26 Whirinaki River – Reduced bed level at cross section 2

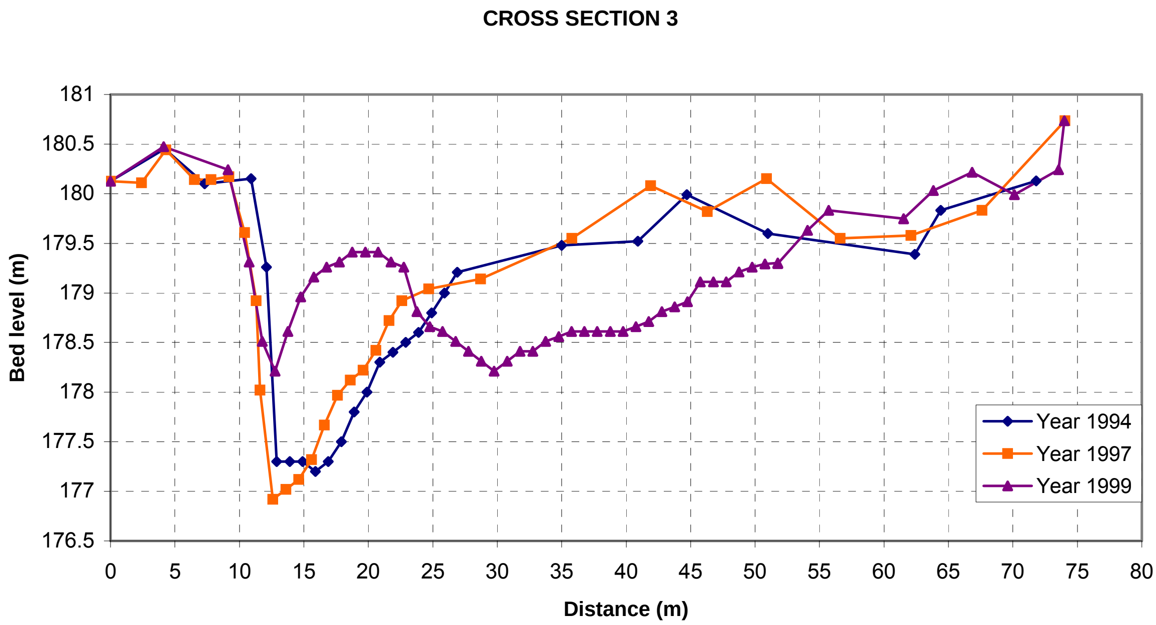

Figure 27 Whirinaki River – Reduced bed level at cross section 3

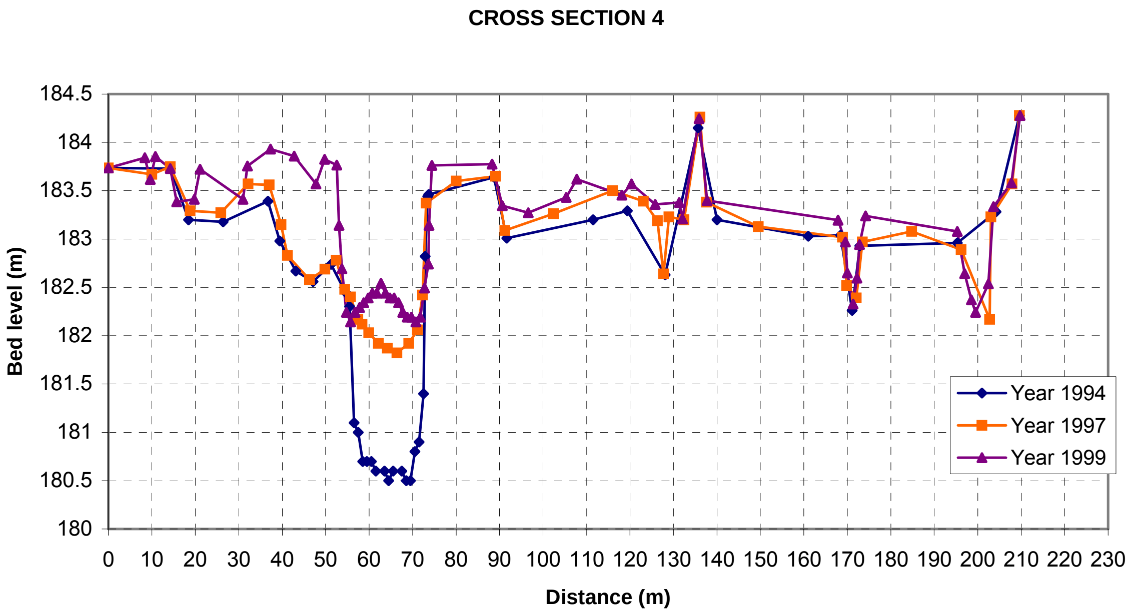

Figure 28 Whirinaki River – Reduced bed level at cross section 4

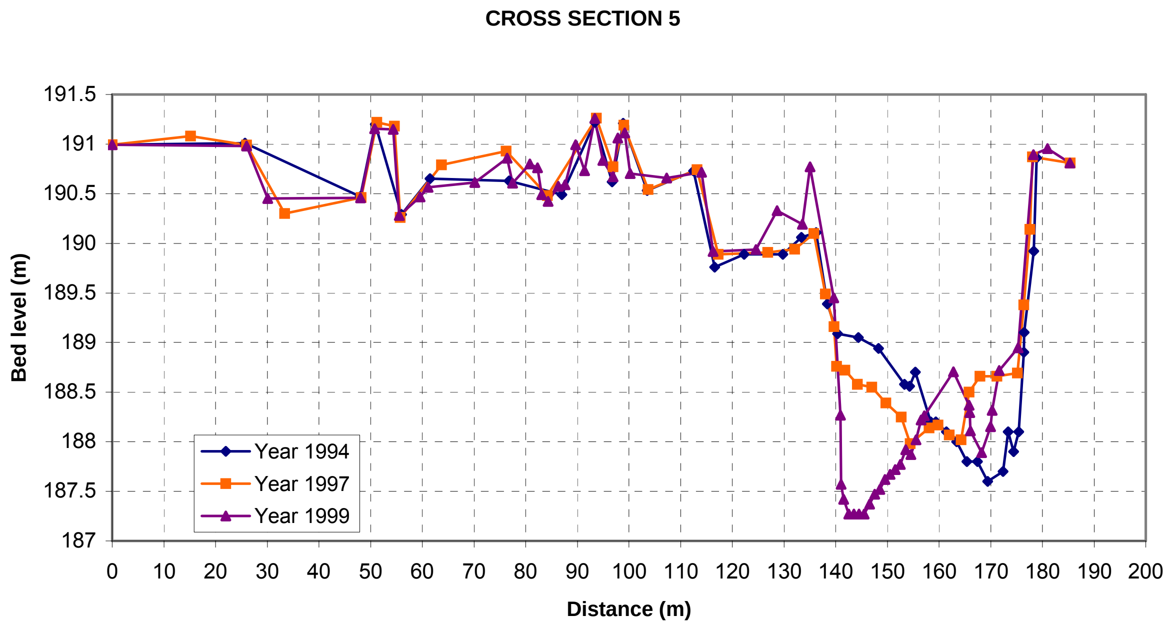

Figure 29 Whirinaki River – Reduced bed level at cross section 5

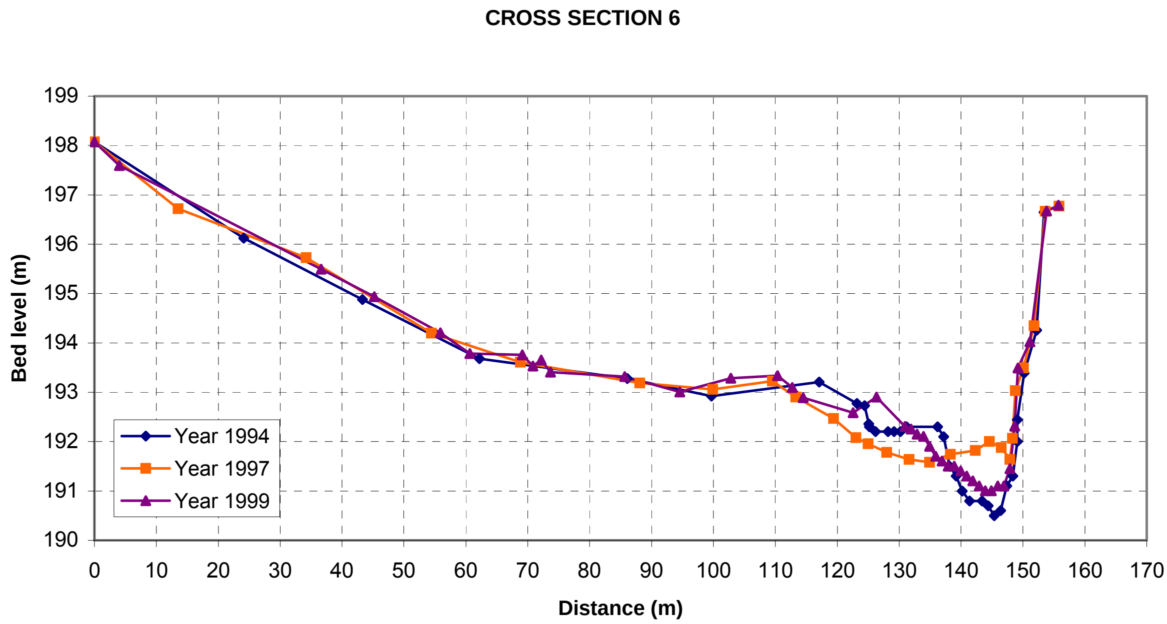

Figure 30 Whirinaki River – Reduced bed level at cross section 6

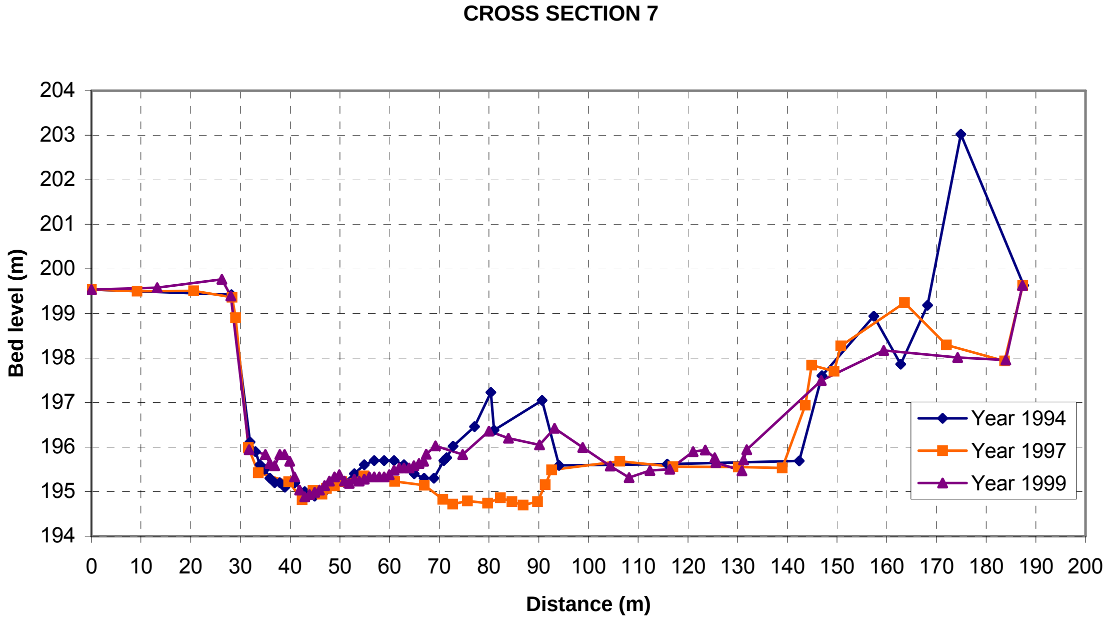

Figure 31 Whirinaki River – Reduced bed level at cross section 7

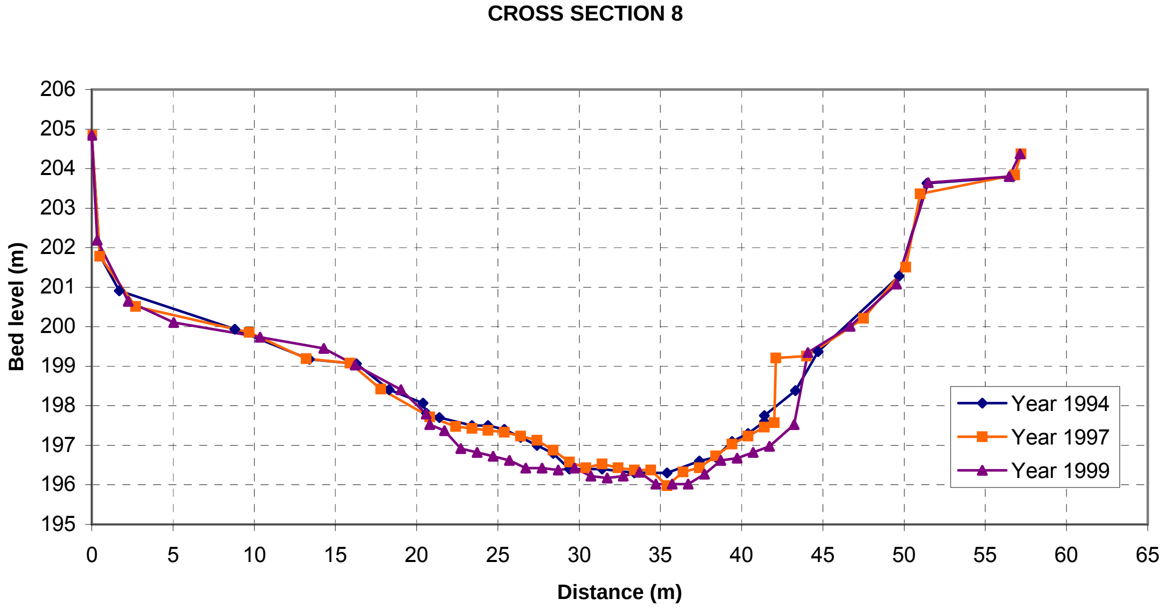

Figure 32 Whirinaki River – Reduced bed level at cross section 8

Chapter 9: References

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Appendices

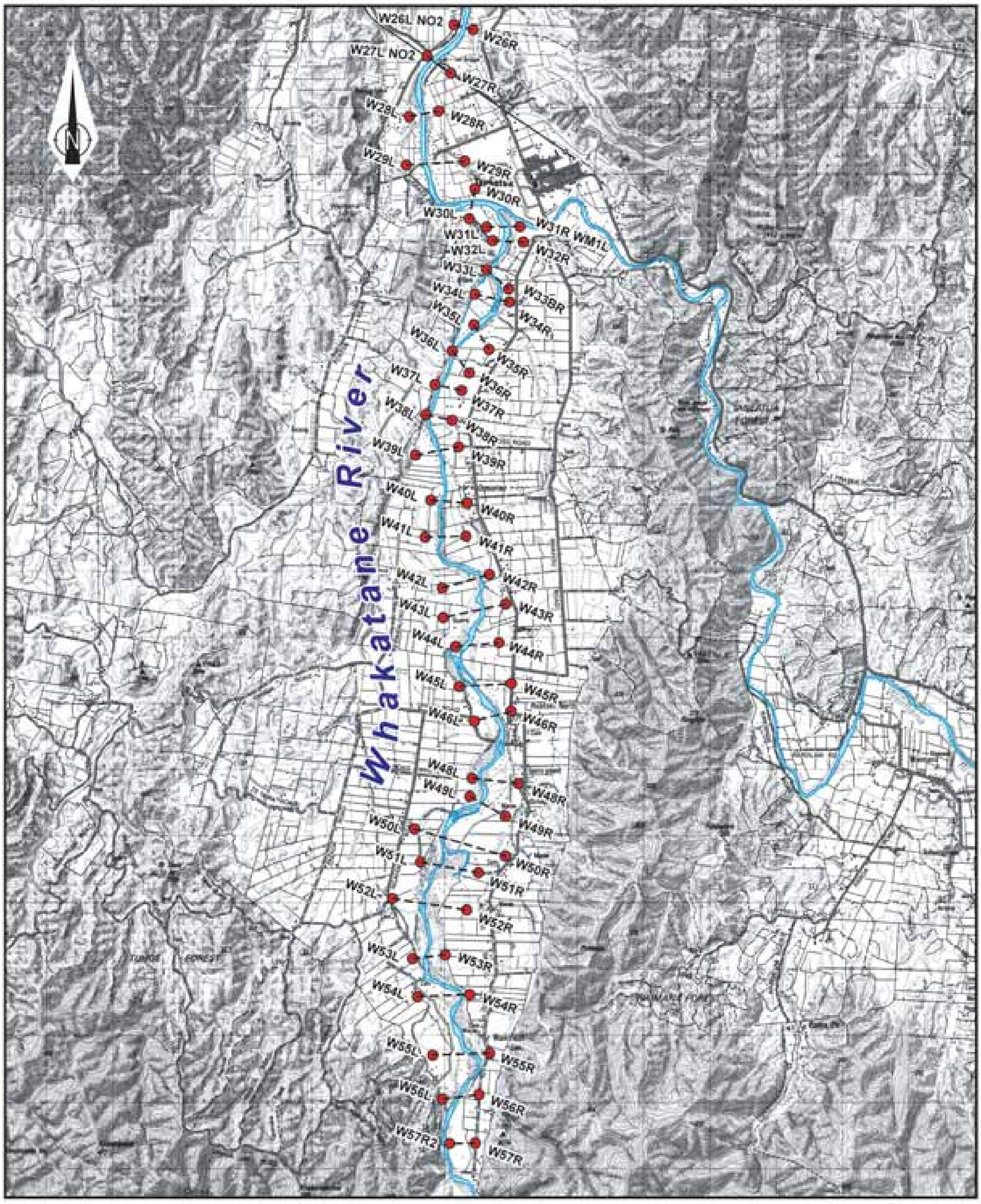
Appendix I – Aerial Photographs of the Whakatane and Whirinaki Rivers

Environment Bay of Plenty REGIONAL COUNCIL

Whakatane River
Cross-section location

W469

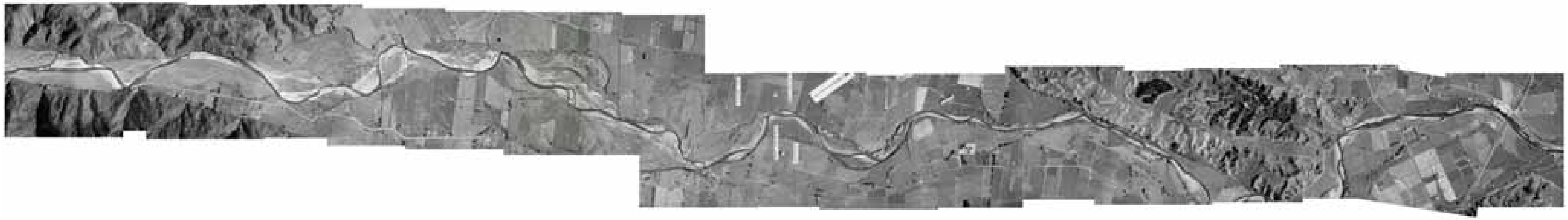
SCALE
0 1.0 2.0 3.0km
1:60 000



Whakatane 1998

Whakatane 1995-1996

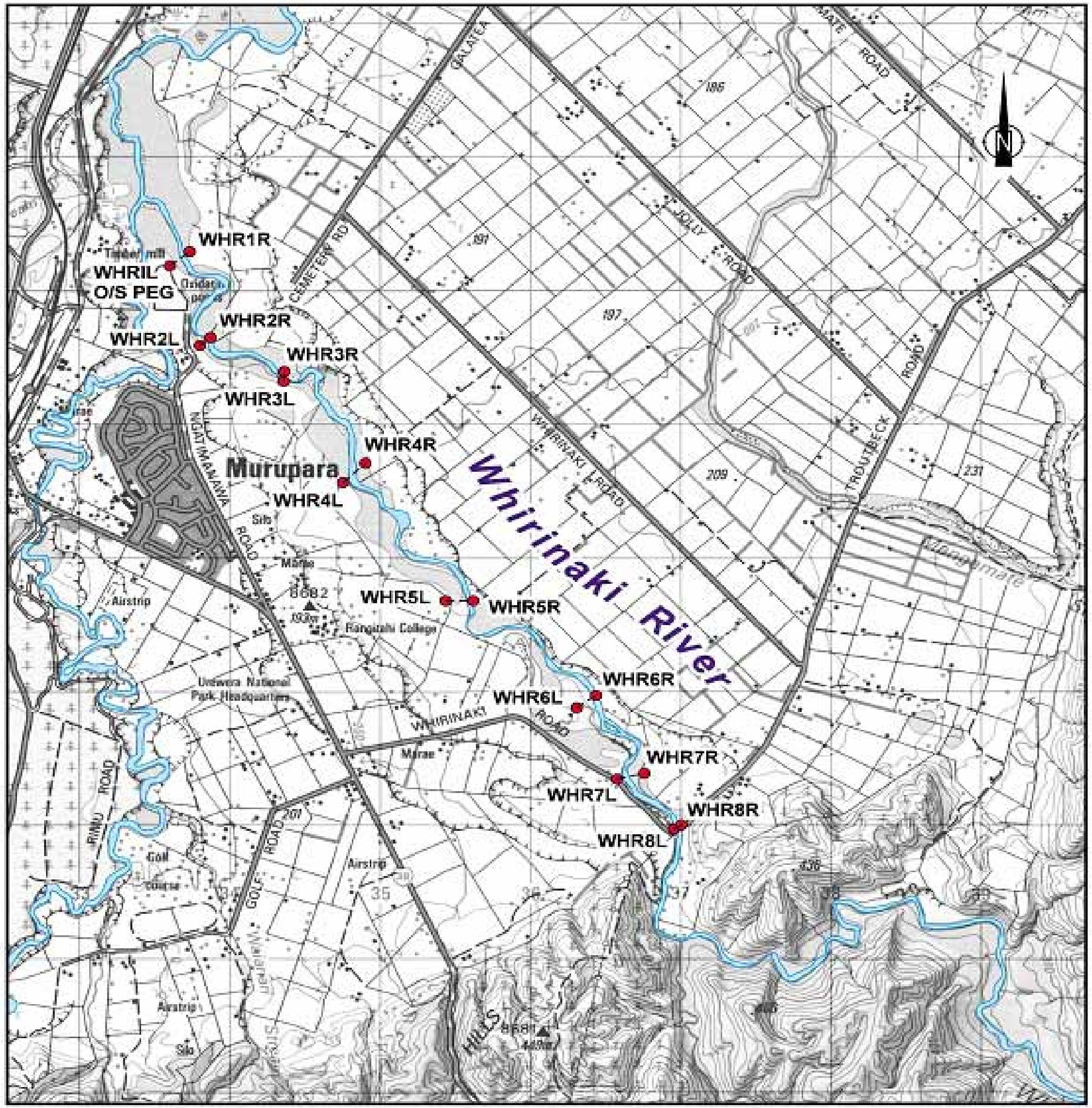
Whakatane 1984



Whakatane 1977

Whakatane 1966

Whakatane 1945



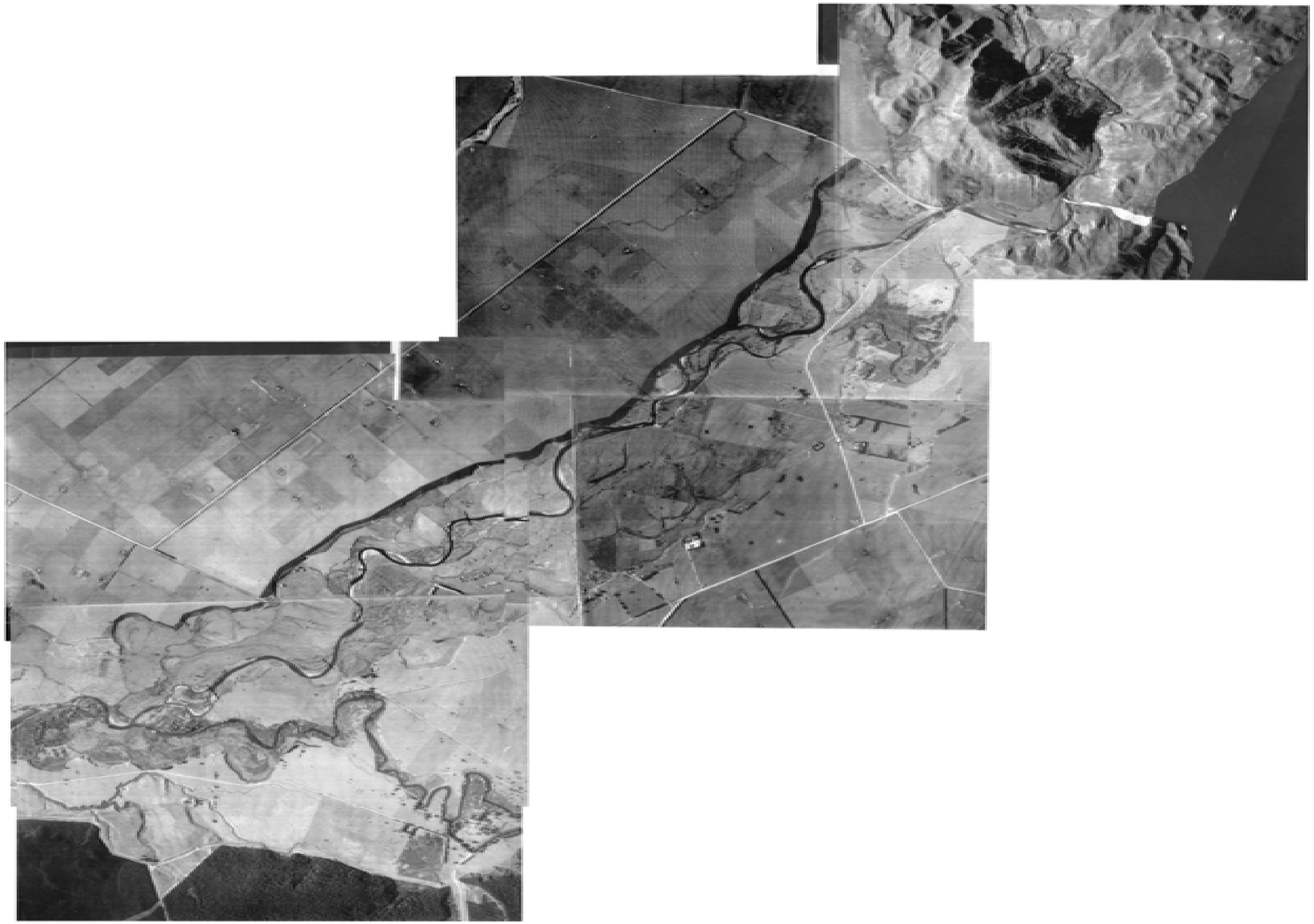
Environment Bay of Plenty
REGIONAL COUNCIL

Whirinaki River

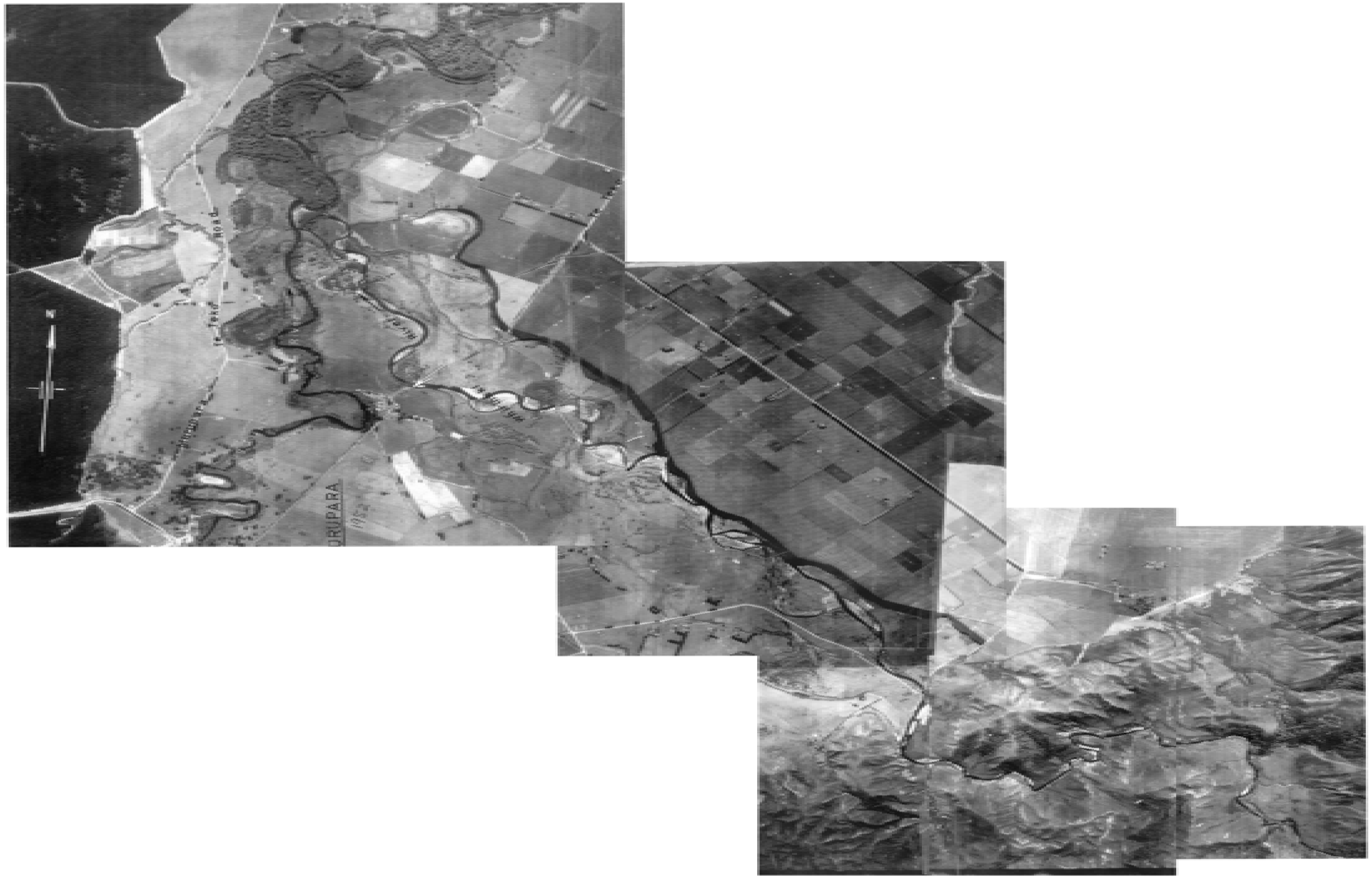
Cross-section location

SCALE
0 0.5 1.0 1.5 2.0km
1:30 000

R733

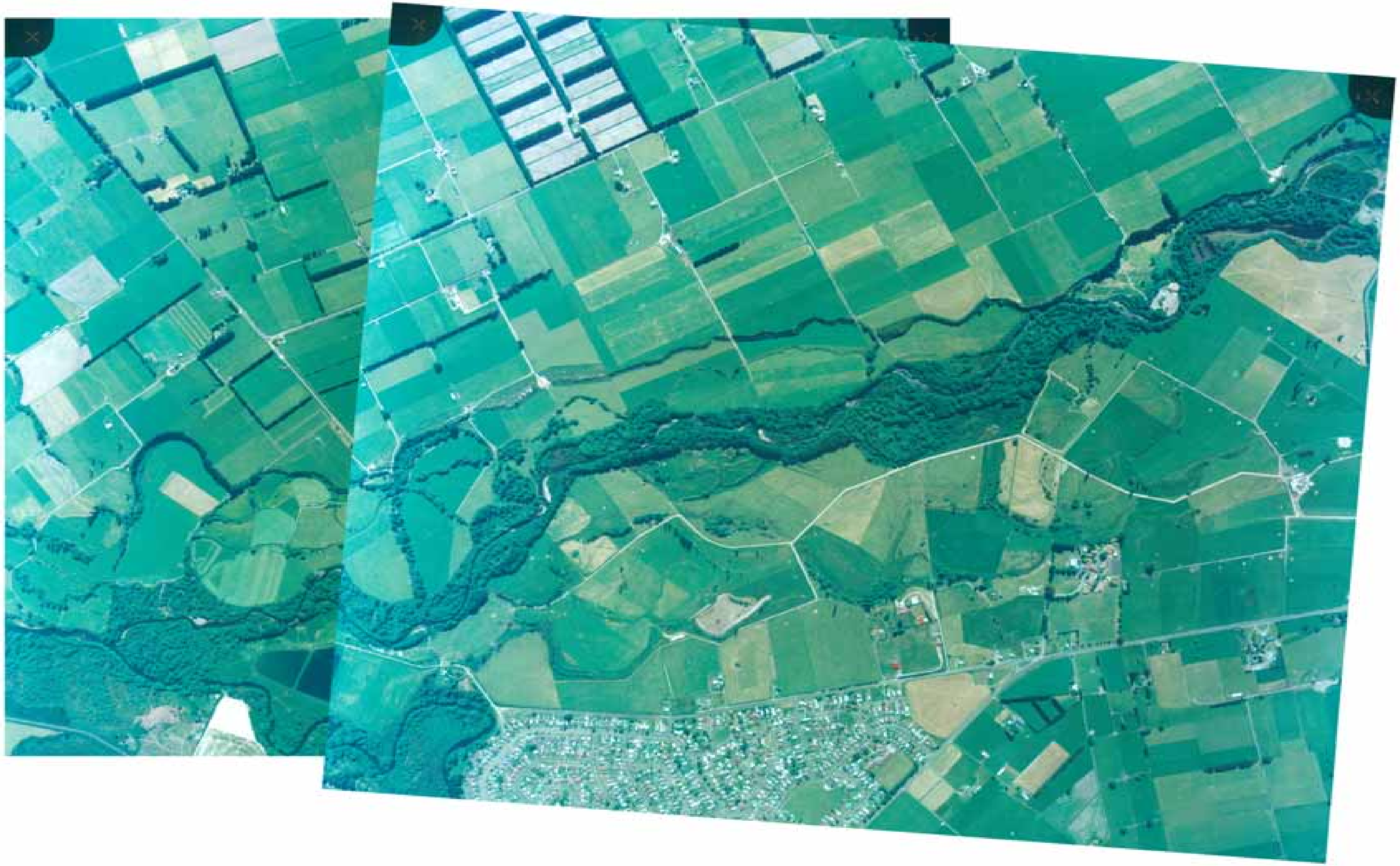


Whirinaki 1941



Whirinaki 1952

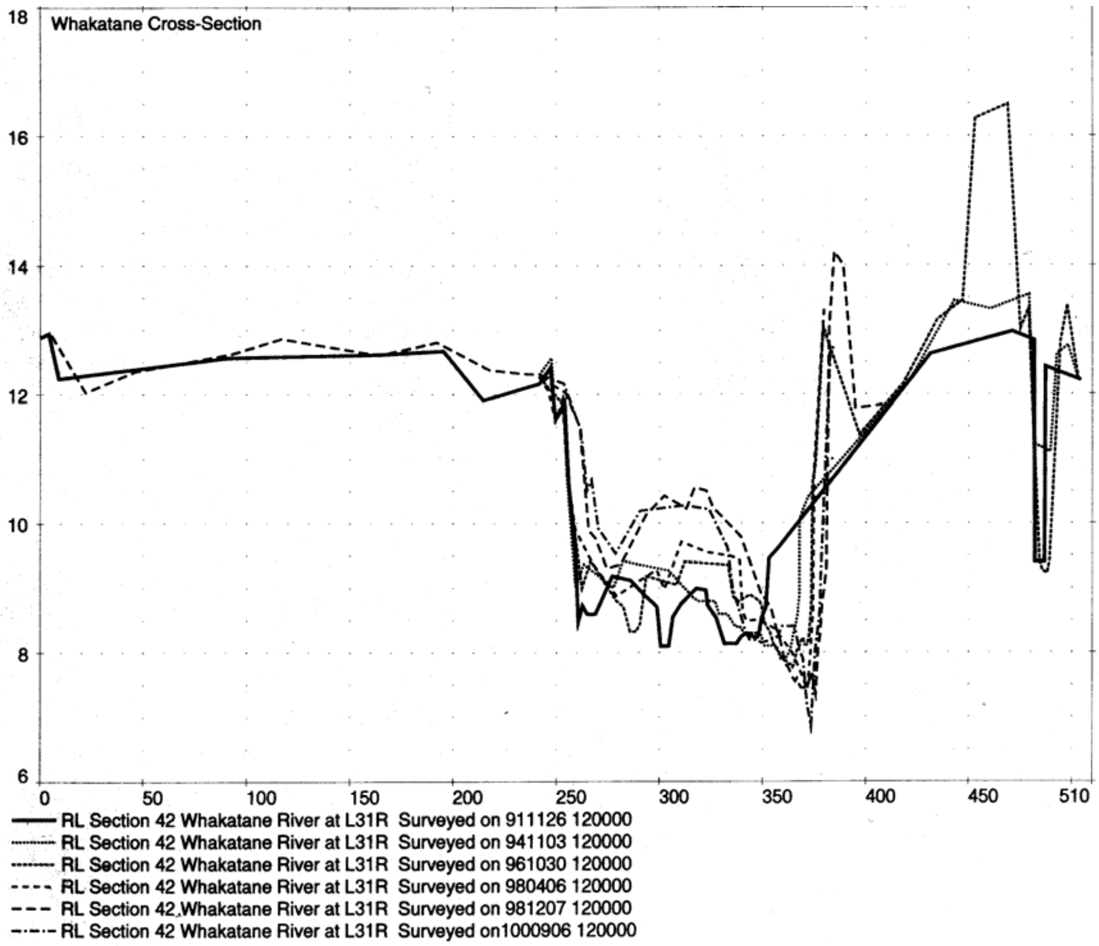
Whirinaki 1994



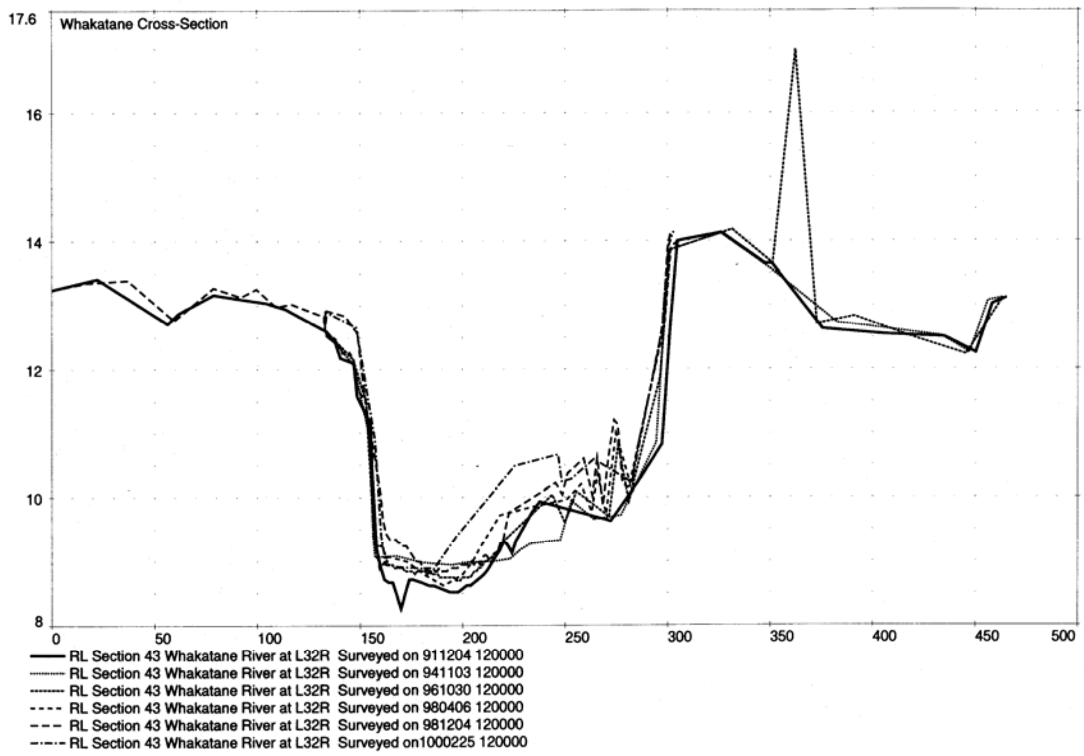
Whirinaki 1997

Whirinaki 1999

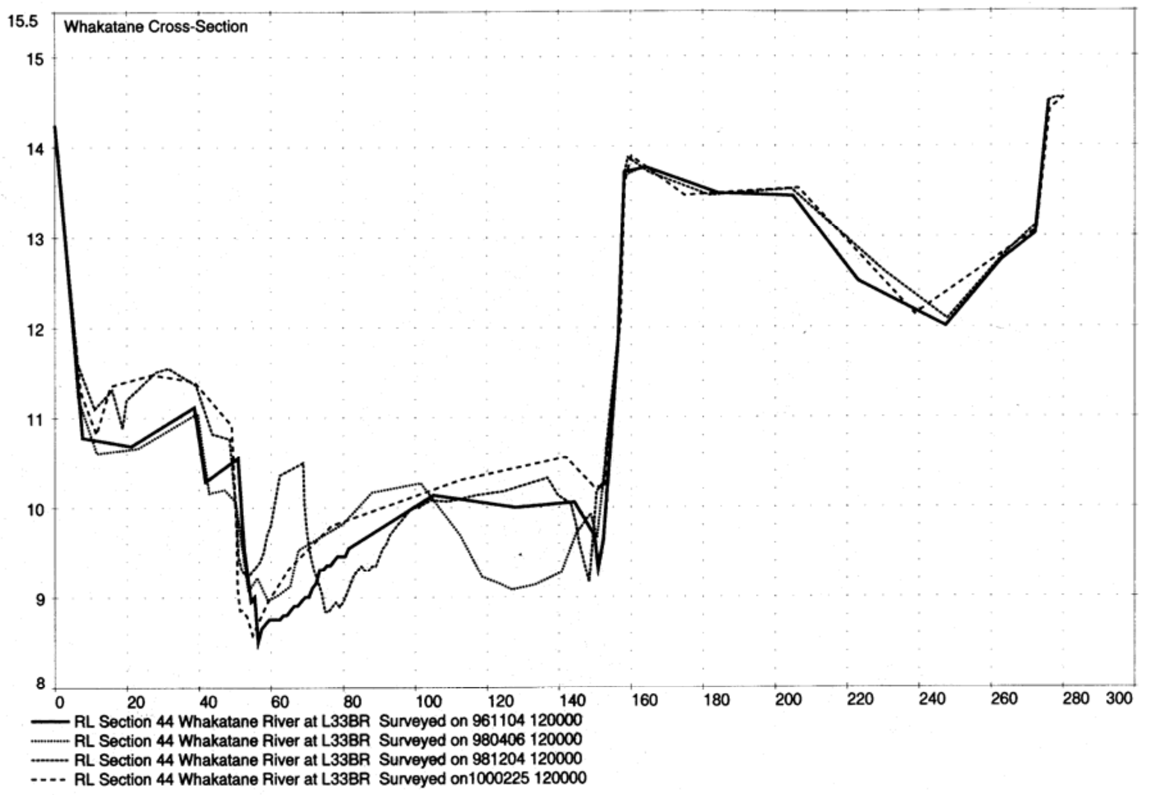
Appendix II – Some of the Middle Reach Whakatane River Channel Cross-sections showing Bed Level Changes over the period 1977 to 2000



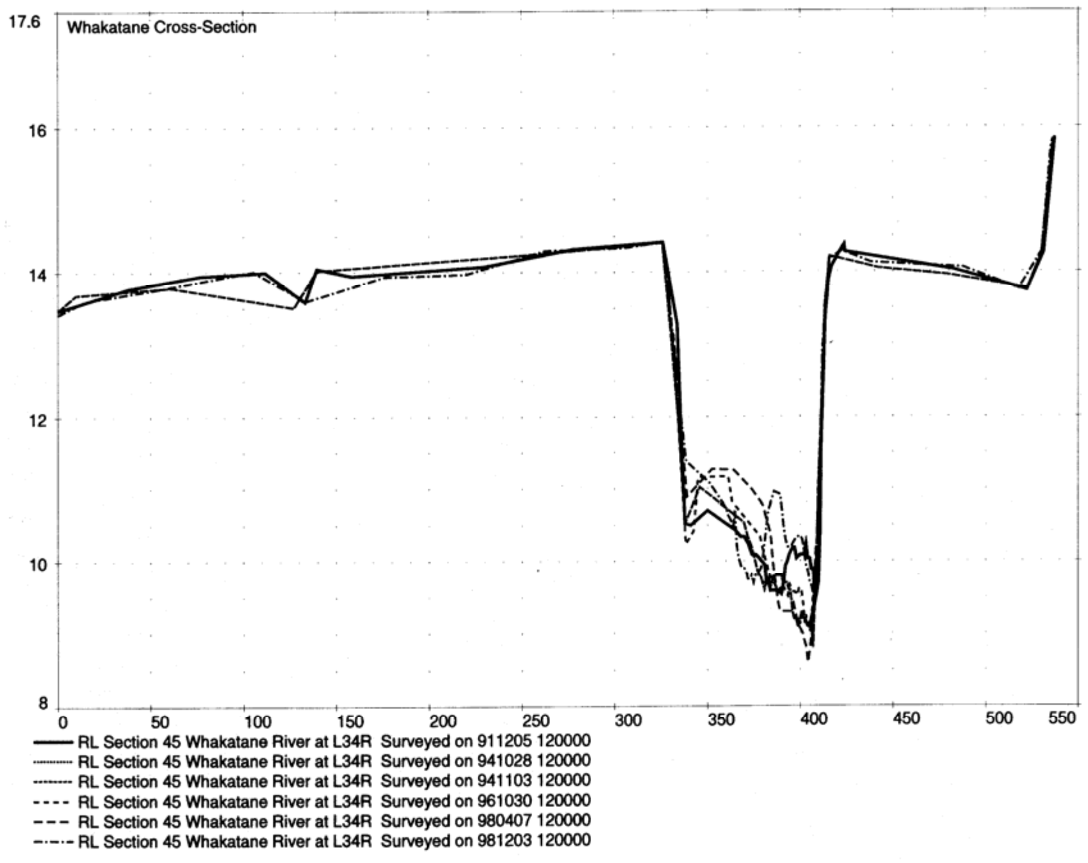
Graph 1



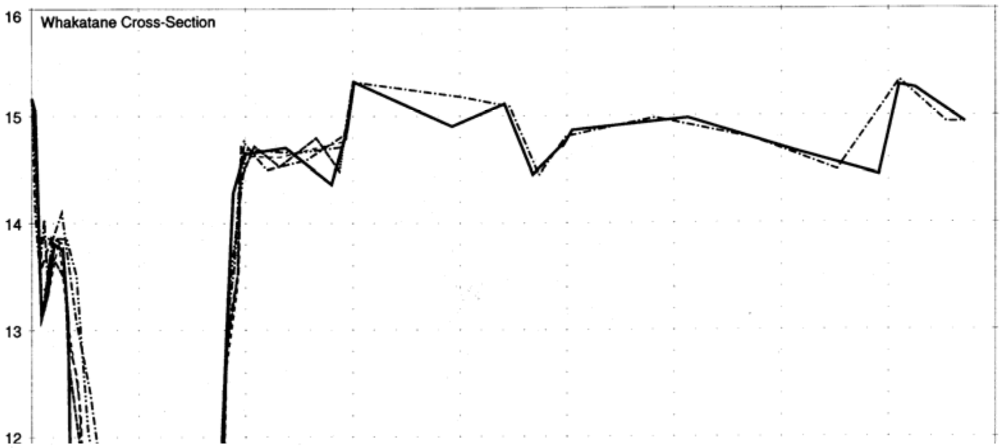
Graph 2



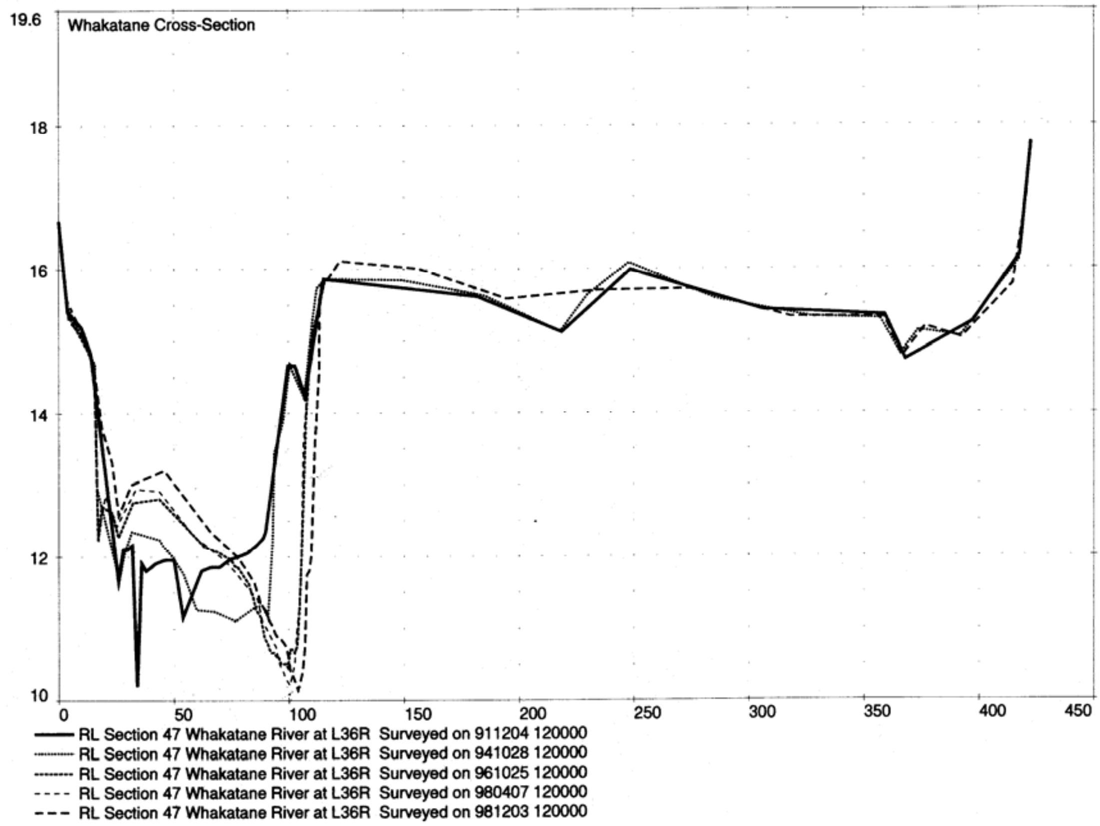
Graph 3



Graph 4

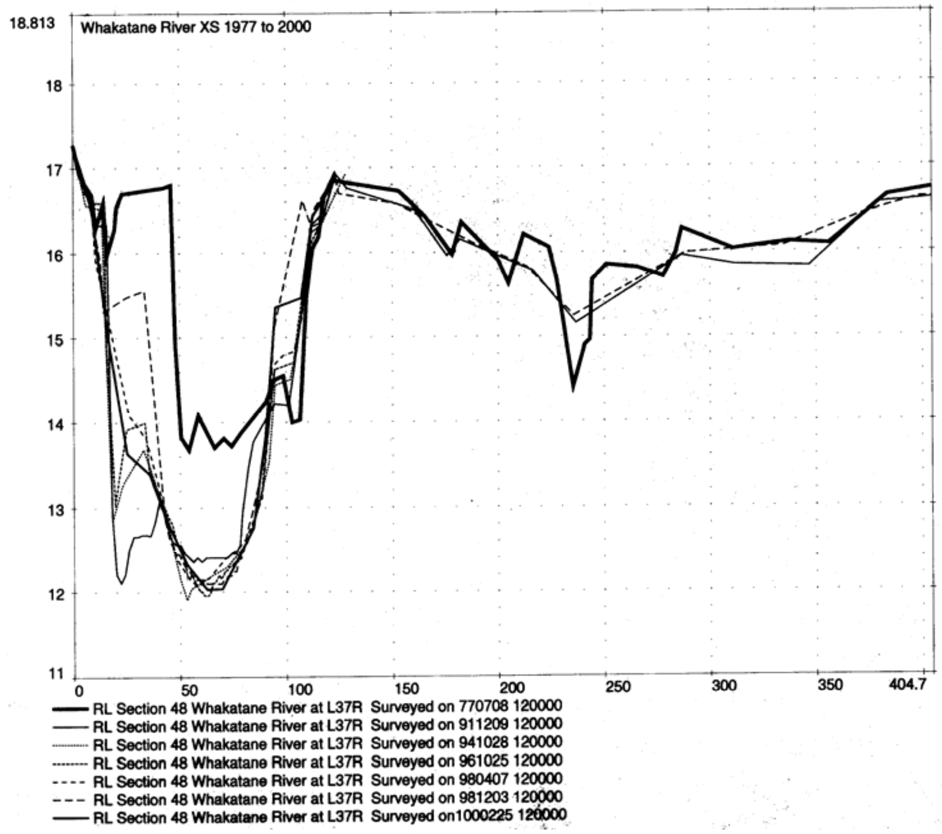


raph

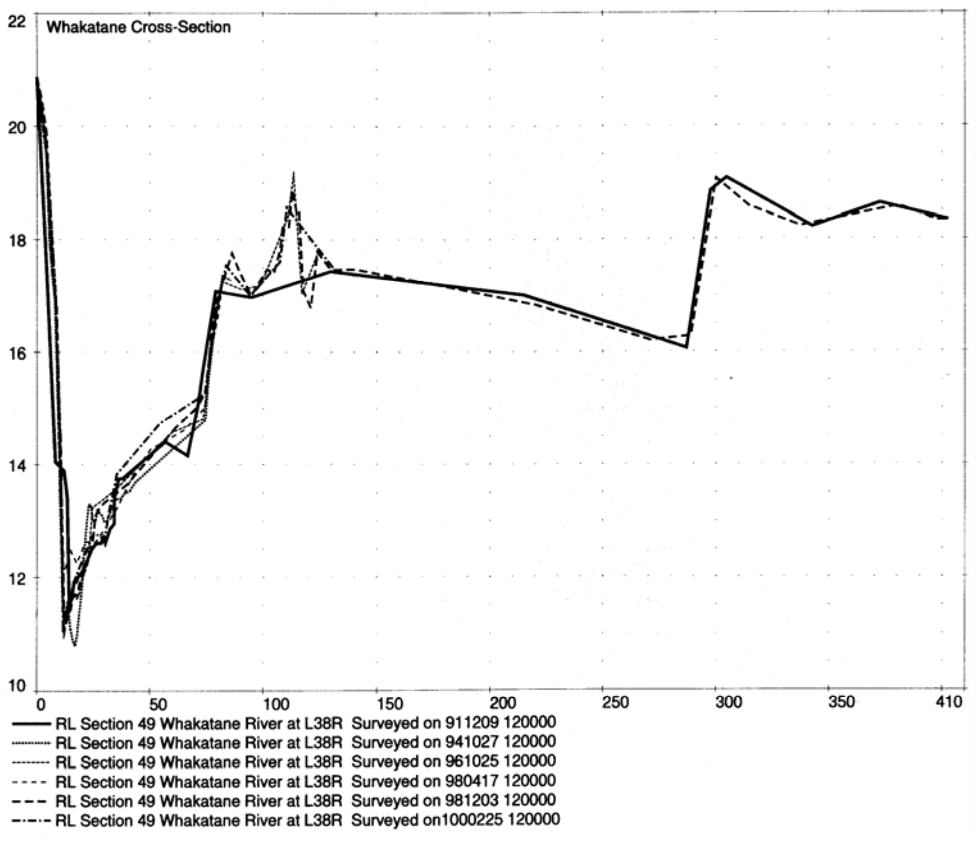


5

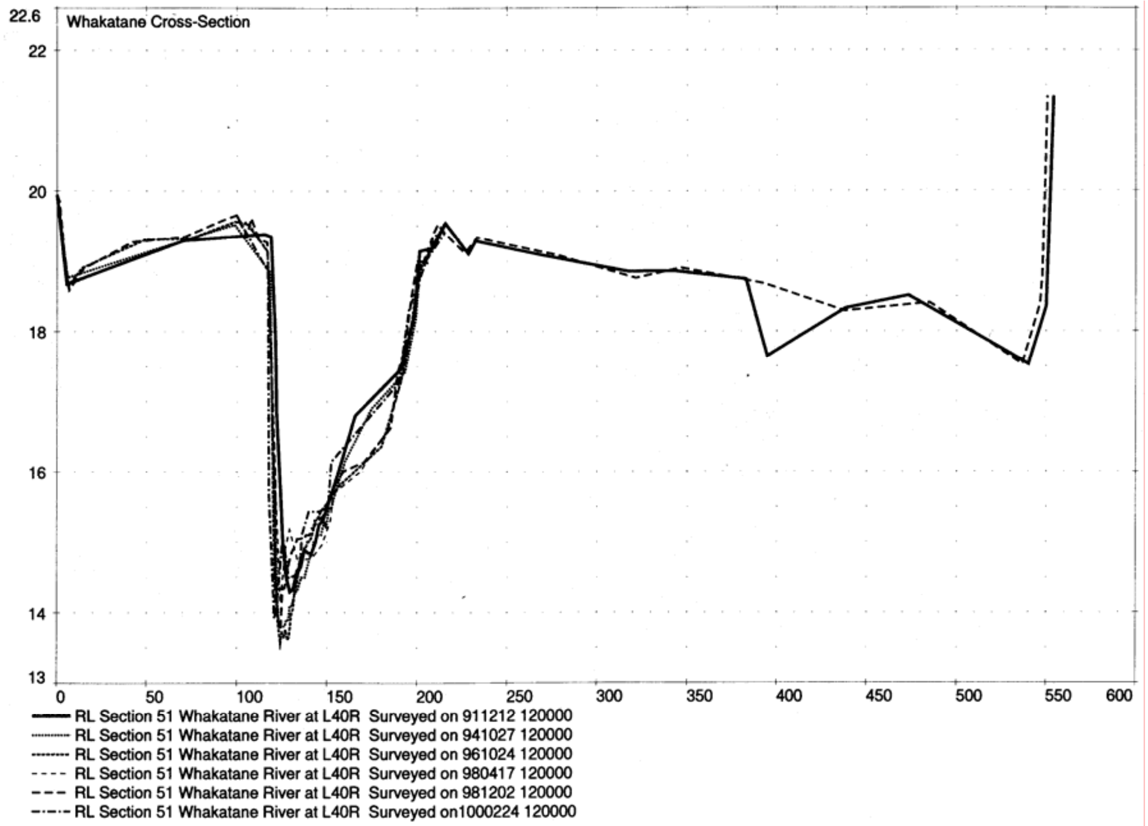
Graph 6



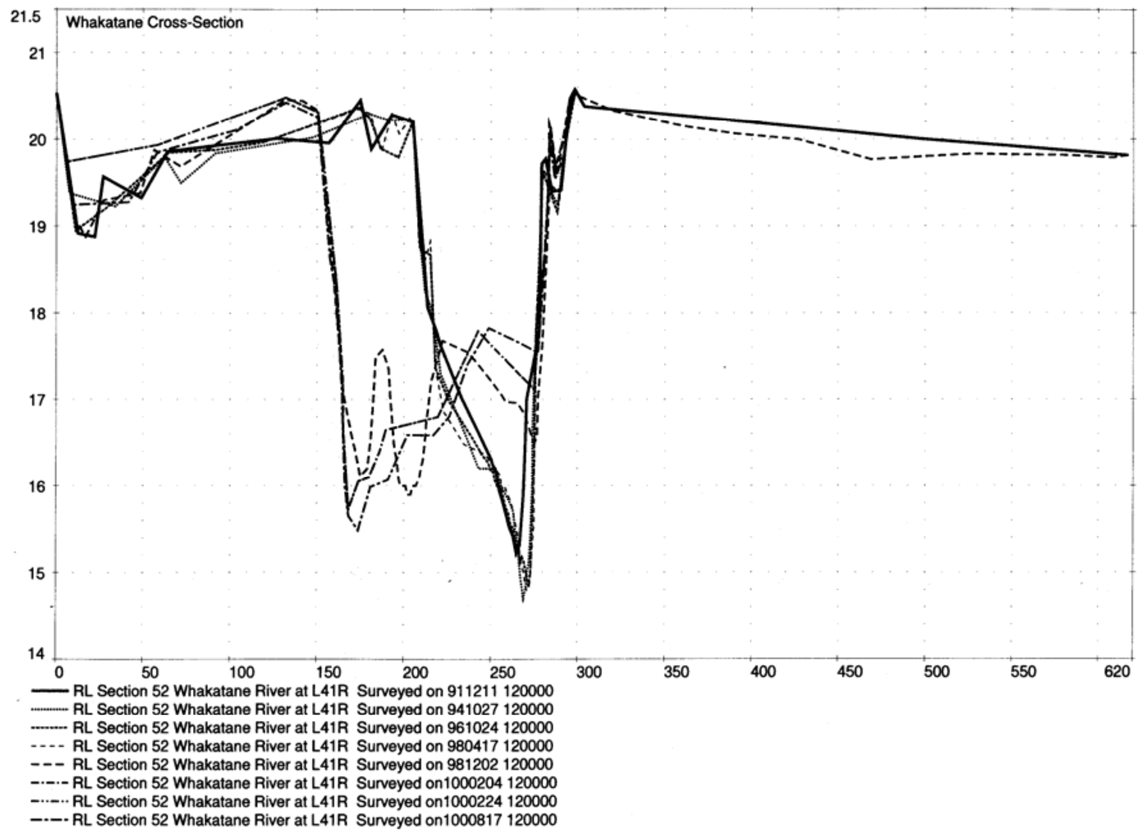
Graph 7



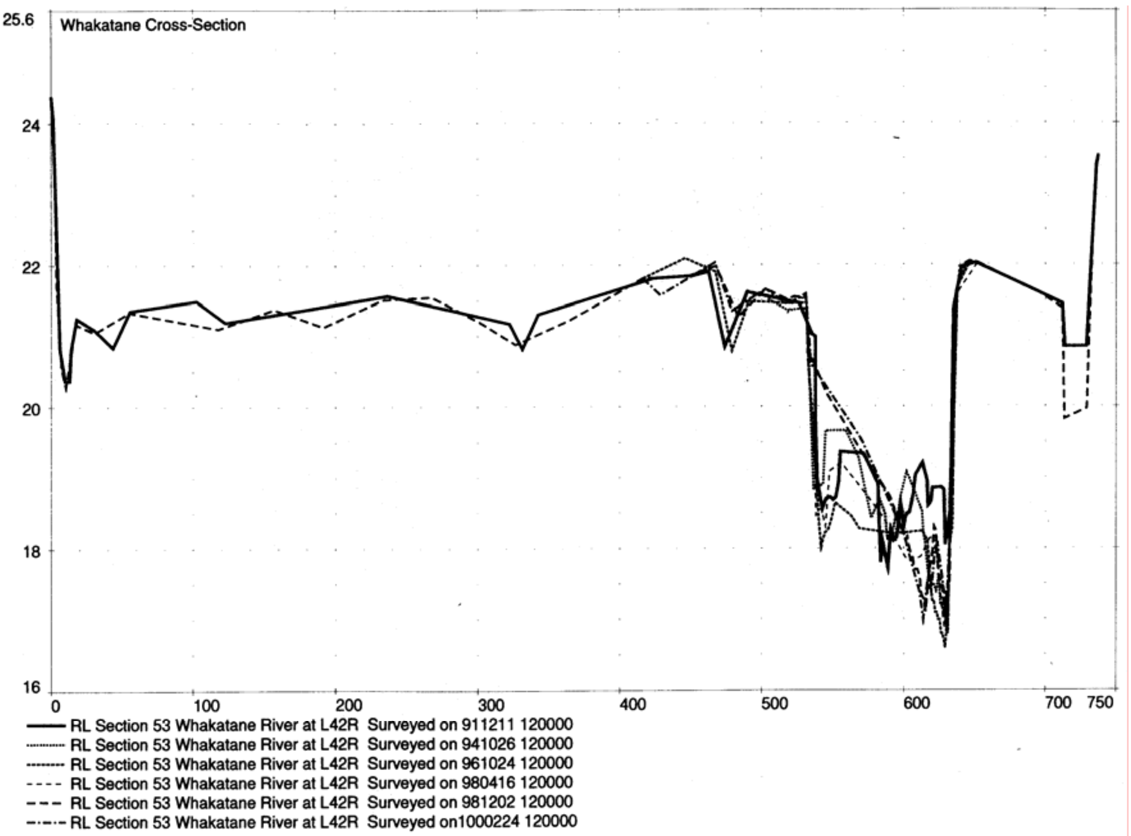
Graph 8



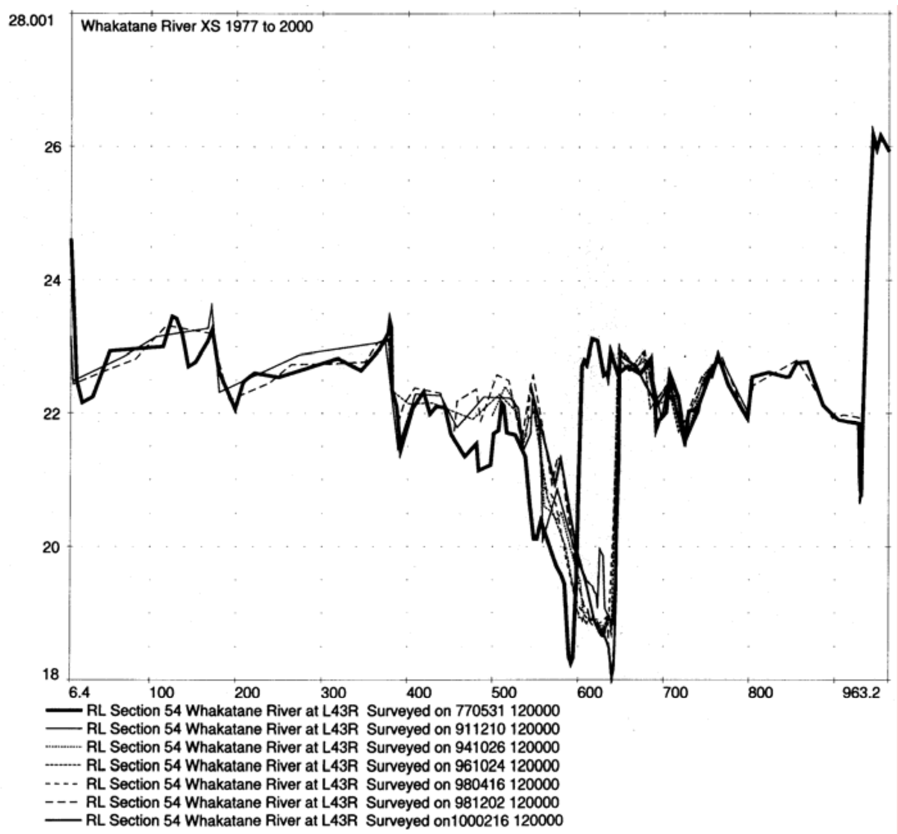
Graph 9



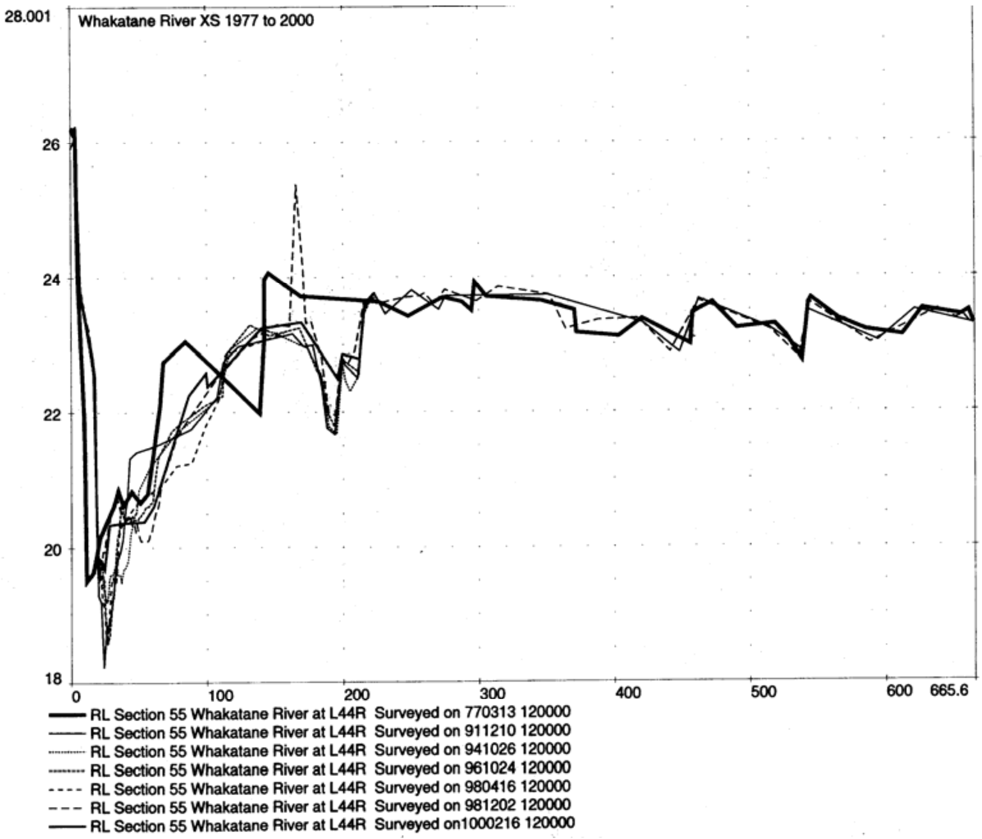
Graph 10



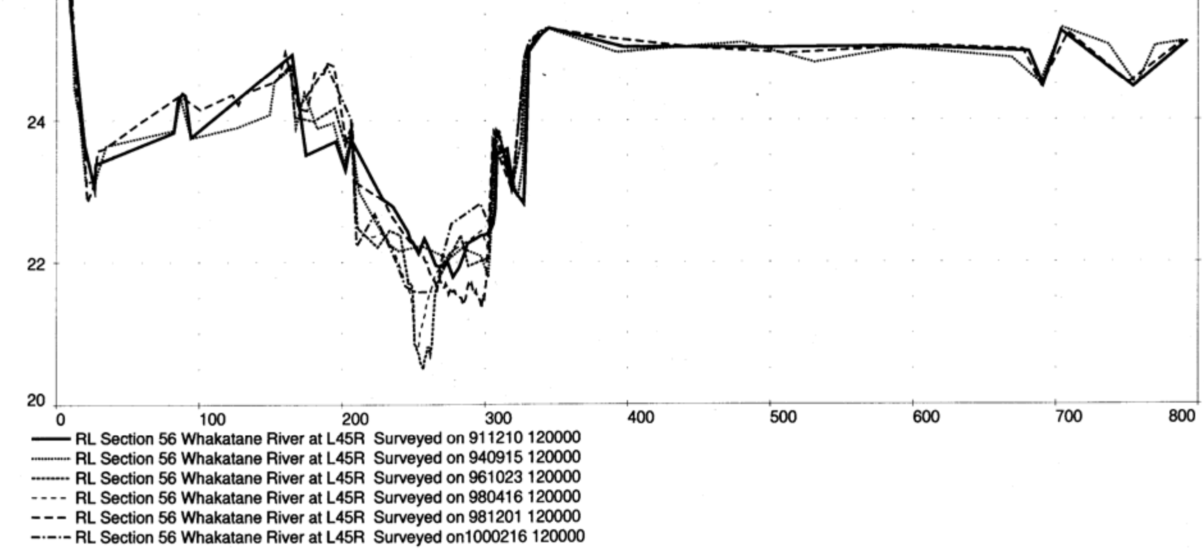
Graph 11



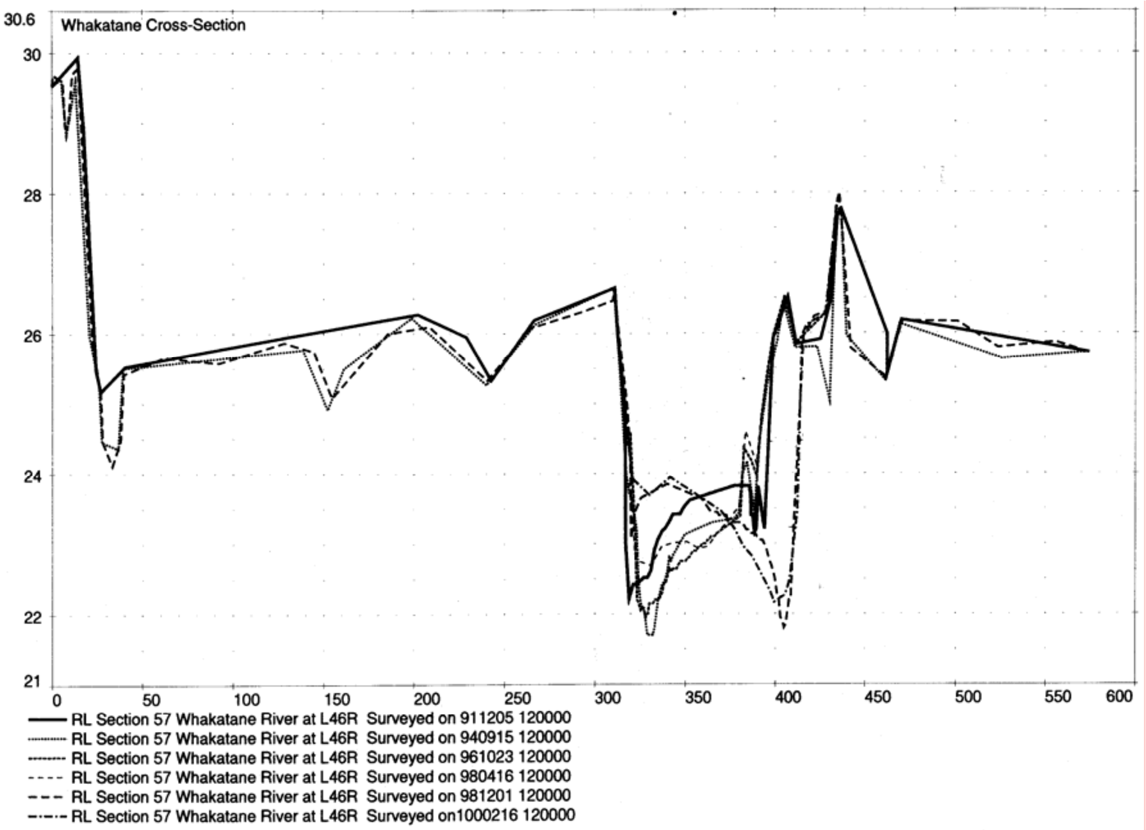
Graph 12



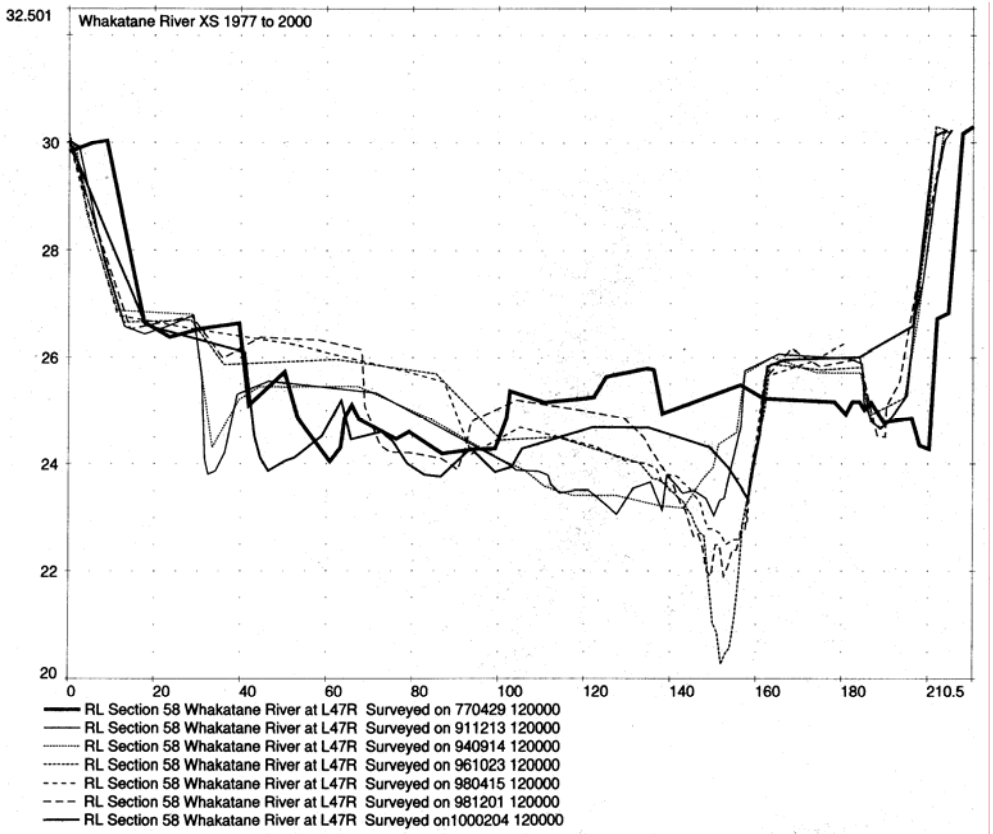
Graph 13



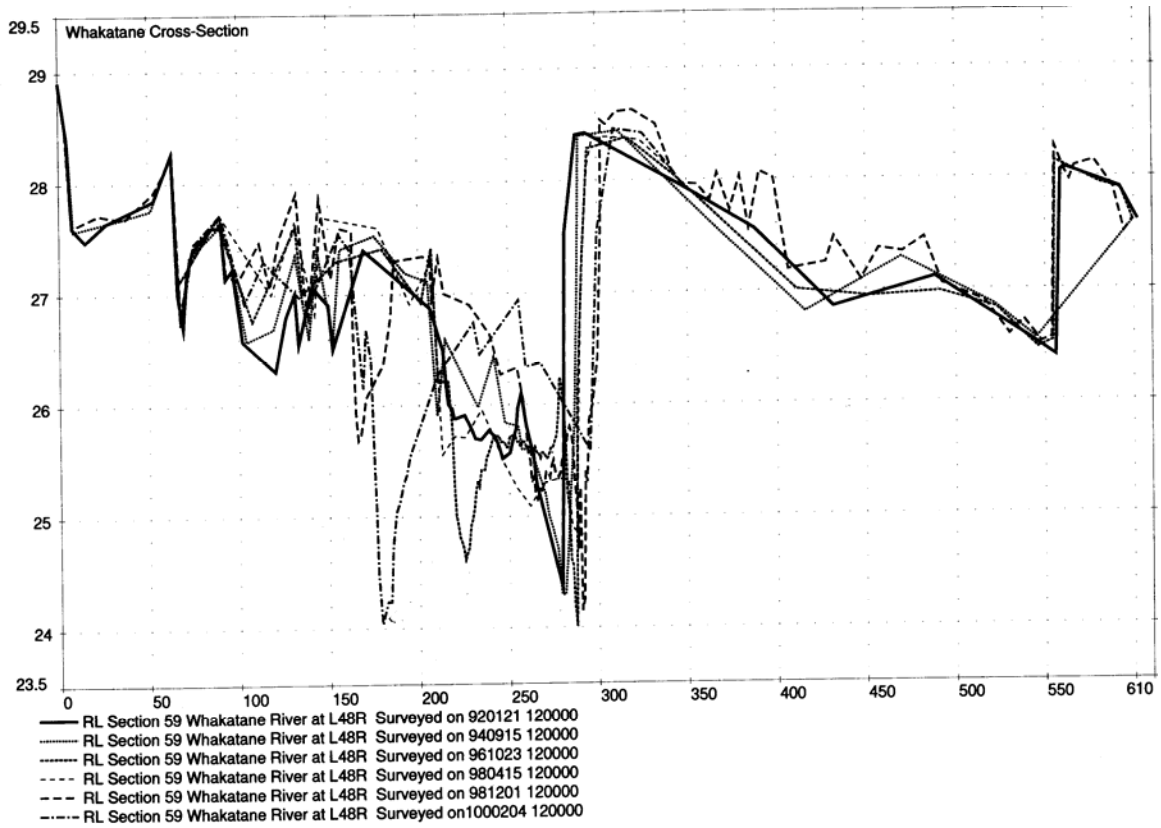
Graph 14



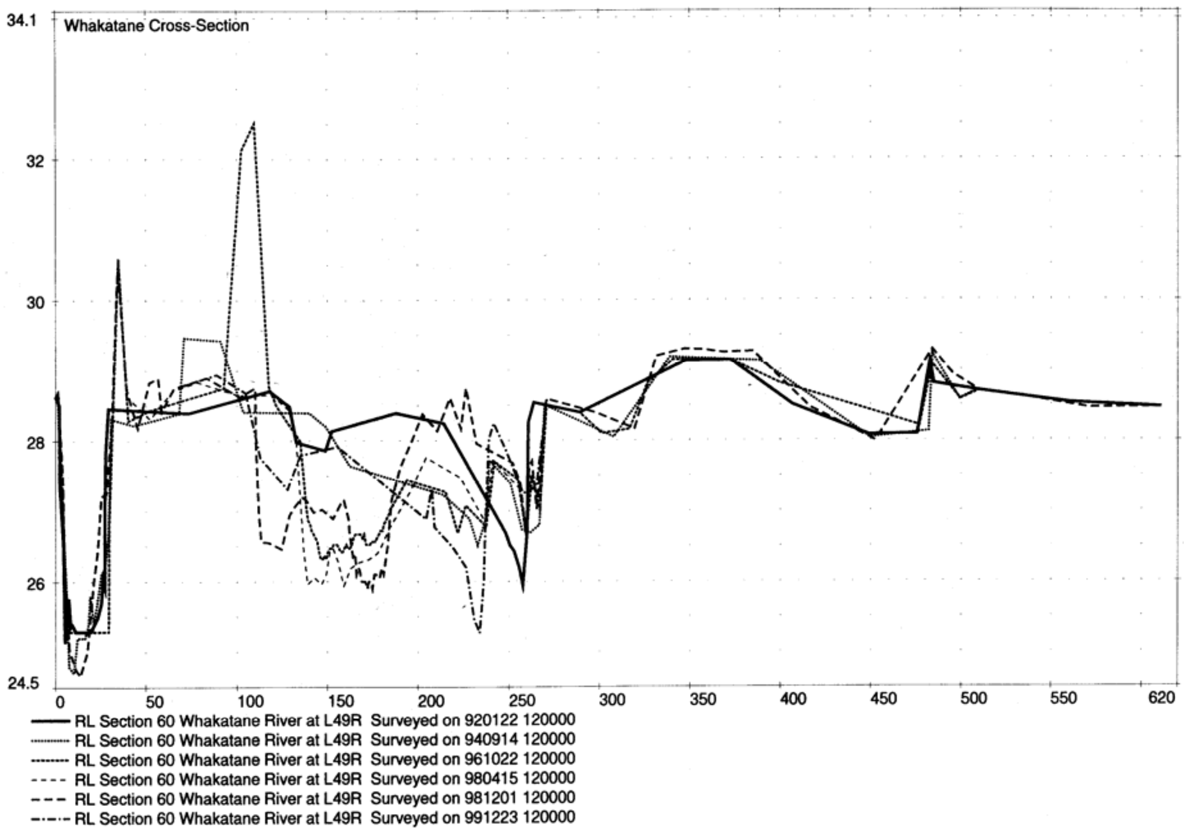
Graph 15



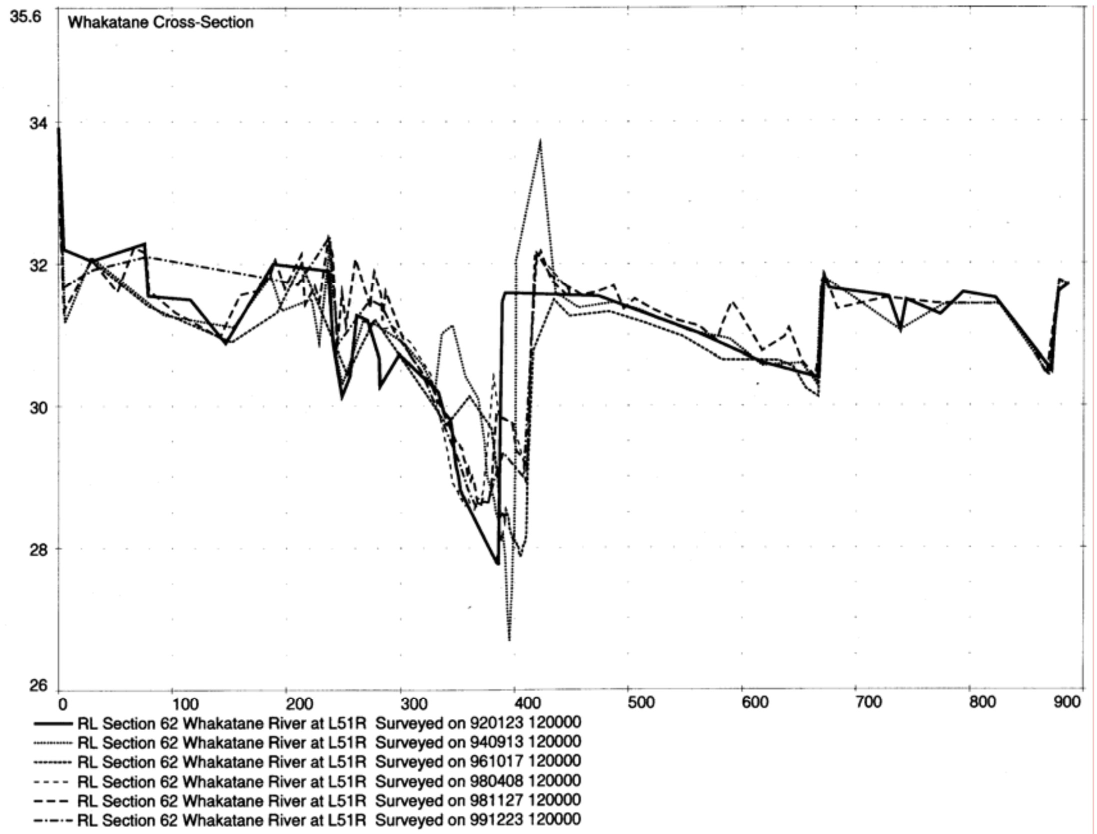
Graph 16



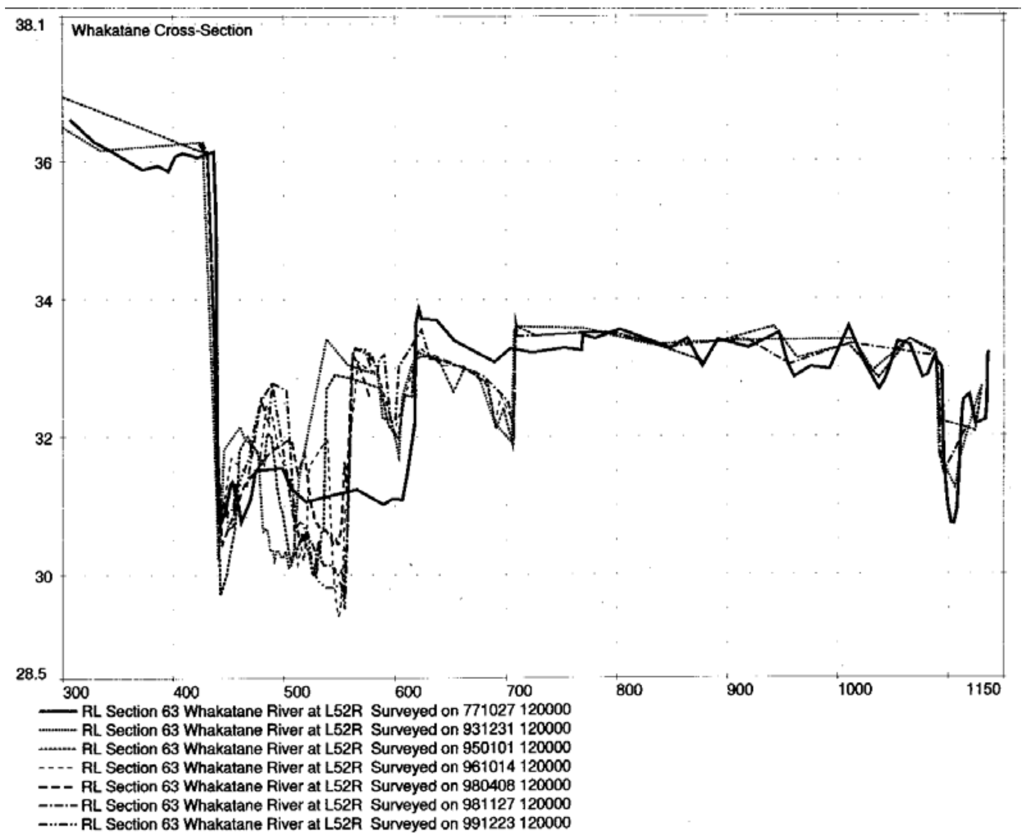
Graph 17



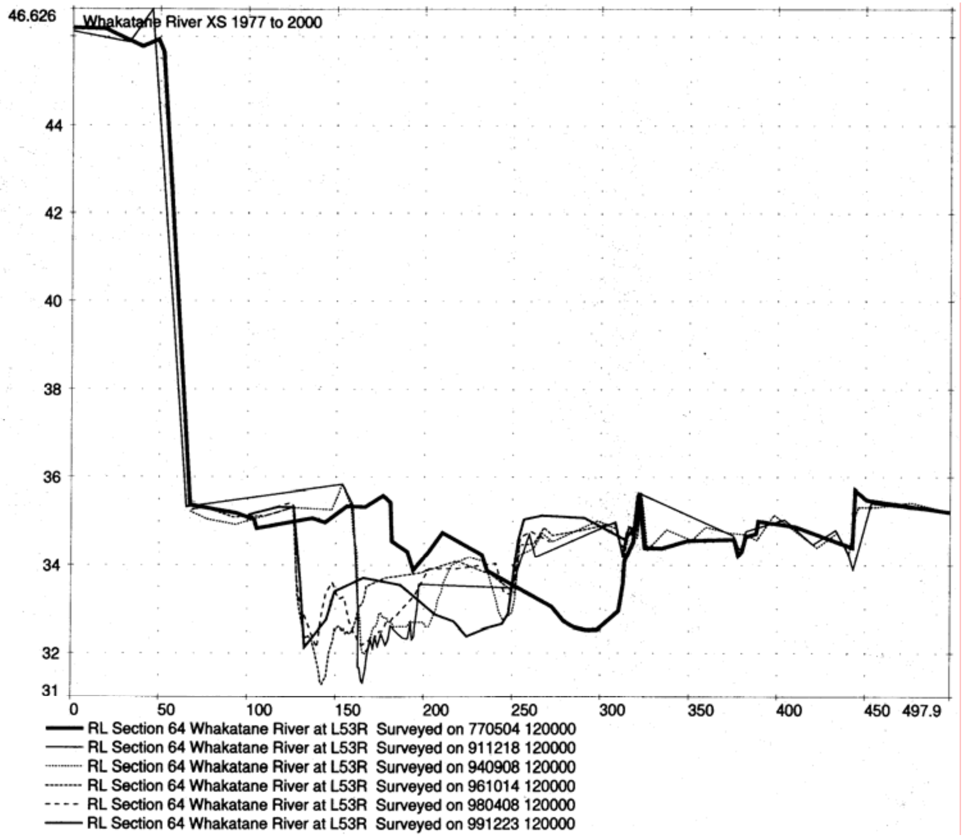
Graph 18



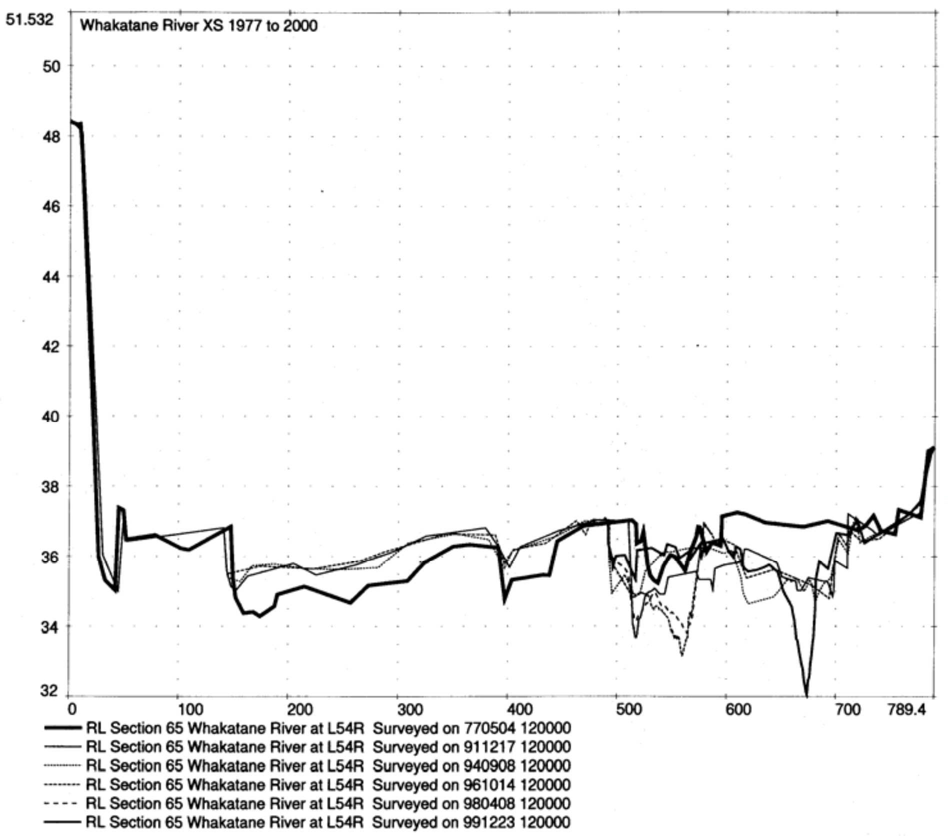
Graph 19



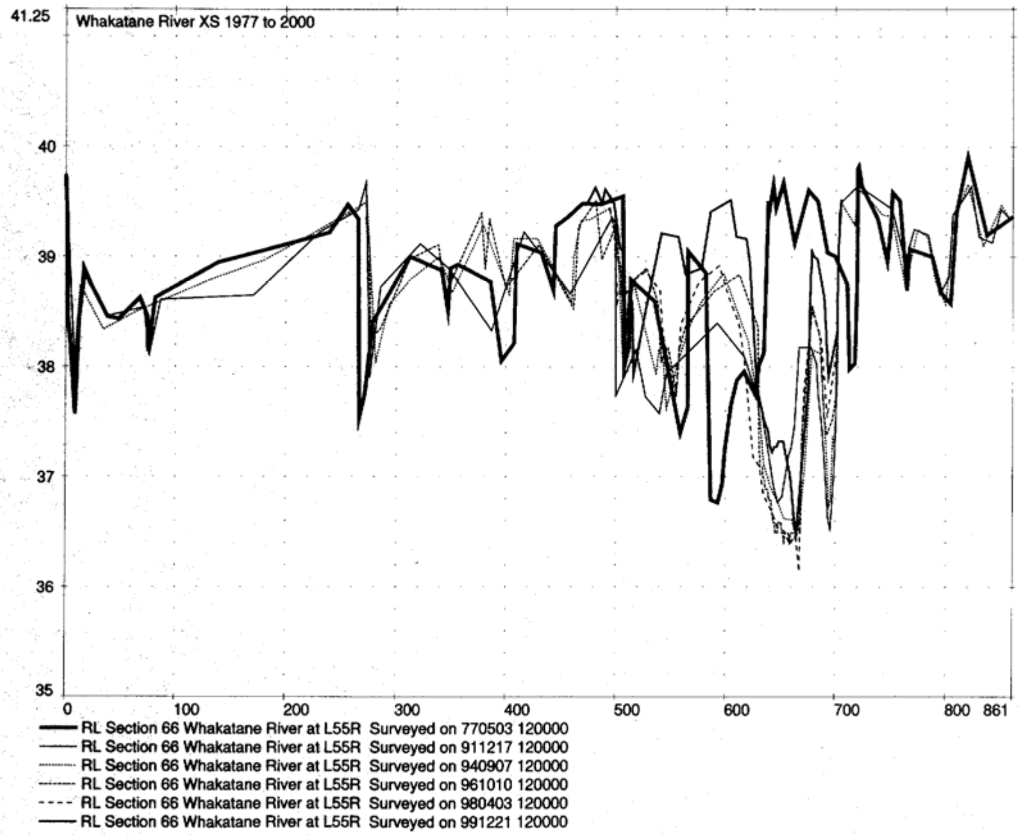
Graph 20



Graph 21



Graph 22


Whakatane River XS 1977 to 2000
41.25
40
39
38
37
36
35
0
100
200
300
400
500
600
700
800
861
RL Section 66 Whakatane River at L55R Surveyed on 770503 120000
RL Section 66 Whakatane River at L55R Surveyed on 911217 120000
RL Section 66 Whakatane River at L55R Surveyed on 940907 120000
RL Section 66 Whakatane River at L55R Surveyed on 961010 120000
RL Section 66 Whakatane River at L55R Surveyed on 980403 120000
RL Section 66 Whakatane River at L55R Surveyed on 991221 120000

Graph 23