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Waipa morphological modelling study Phase 3: Analysis and modelling

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Waipa Morphological Modelling Study

Phase 3: Analysis and Modelling

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Executive summary

Waikato Regional Council (WRC) has commissioned NIWA to carry out a morphological modelling study on the Waipa River to provide guidance on how the Waipa River channel is likely to adjust in the future as a large volume of bed material moves down the river. This 'slug' of bed material is the result of sediment generated from the Tunawaea Landslide, which occurred in 1991, and subsequent erosion of bank and river terrace material induced by raised bed levels resulting from the Tunawaea slip material migrating down the Waipa River. Understanding how the Waipa channel is likely to adjust in the future will help WRC to plan effective river management in response to these adjustments.

In order to build a morphodynamic model of the Waipa, various input data are required, and much of this has been collected during previous phases of this study. Phase 1 involved the collection of survey data in the Waipa River, which provide the underlying topography for the model. This phase was completed in November 2013. Phase 2 involved collecting sediment data required for the model, surveying the Tunawaea Stream, surveying flood level marks and also building a preliminary model of the upper Waipa. This phase was completed in August 2014. Phase 3 is the focus of this report, and describes the morphodynamic modelling approach and results, analysis of the Waipa River's adjustment over the period following the landslide, interpretation of model predictions of future adjustment and recommendations for future river management.

To use a morphodynamic model to predict future changes in the Waipa River, the model must first be able to reproduce the adjustments that have occurred in the period following the landslide. In this study we first gathered existing data (historic cross sections, aerial photographs and previous reports) that describe how the Waipa River has adjusted from the time prior to the landslide through to the present day. We then constructed a 1-dimensional morphodynamic model of the Waipa River using NIWA's Gravel Routing And Textural Evolution (GRATE) model. The GRATE model was calibrated by comparing model results from a 1990-2015 simulation run with the observed historic adjustments.

The results of the modelling and analysis were assessed reach by reach to identify the main historic and future changes in the Waipa. These results show that gravel from the Tunawaea Landslide rapidly entered the Waipa river system following the landslide dam break in 1992. This gravel moved quickly through the gorge reach (the 3 km downstream of the Tunawaea confluence) and raised bed levels significantly in the reach downstream of the gorge, as far as the partly confined reach upstream of the Rewarewa access point (approximately 15 km downstream of the Tunawaea confluence). Erosion of the Taupo pumice terraces (located 5-6 km downstream of the Tunawaea confluence) occurred when the river be aggraded to the point where it could erode laterally into the terrace material. This has since been controlled by engineering works. Overall, the signature of the Tunawaea Landslide has been largely limited to the upper parts of the study reach, and its spread downstream from there has been dispersive rather than advective. In the lower part of the study reach, downstream of Toa Bridge, the main drivers of change in the period since the Tunawaea Landslide appear to be historic channel straightening and gravel extraction.

In terms of future adjustment, our results predict gradual re-working of the Tunawaea Landslide gravel deposits, both in the Tunawaea and in the upper Waipa, but predict little effect on future bed levels in the Waipa (up to 0.1 m) as a result of this. However, we do predict ongoing degradation in the reach between Toa Bridge and Rendall's Bridge (approximately 9 km downstream) as a result of adjustment caused by a historic meander cut-off just downstream of the location of Rendall's Bridge.

We also predict ongoing aggradation from Rendall’s Bridge to 1-2 km upstream of the Otorohanga Weir as a result of the same meander cut-off. Stable bed levels are predicted immediately upstream of the Otorohanga Weir and possible ongoing degradation downstream of the Otorohanga Weir, although this is beyond the study area limit and model results are uncertain for this location.

Looking at the Waipa as a whole, the effects of the Tunawaea Landslide seem to have stabilised. The model predictions show that future problematic bed level change as a result of this landslide are unlikely. It should be noted, however, that similar landslide events have occurred previously and are likely to occur again.

Downstream of the landslide effects, the model predictions that could be a cause of concern are ongoing erosion from upstream of Toa Bridge to Rendall’s Bridge and deposition from Rendall’s bridge down to 1-2 km upstream of Otorohanga Weir. Peak erosion of -0.5 m and deposition of +0.3 m compared to current mean active channel bed levels are predicted in these reaches by 2050, with -0.9 m and +0.5 m predicted by 2105.

It is recommended that council staff review the predictions of bed level change in this report with respect to the likely effects on flood risk and bank stability. This will enable the identification of any areas where the predicted future changes are likely to cause significant problems. Ongoing monitoring of bed levels via cross-section surveys should continue on a regular basis with more frequent monitoring (5 yearly or more frequent) at areas of concern and less frequent (e.g., 10 yearly) over the full study reach. Following each survey, cross-sections should be compared to extract trends of mean bed level change and identify any cross-section shape changes. There would be value in extending the modelling and analysis carried out for this study further downstream to investigate degradation downstream of the Otorohanga Weir and predict future trends in bed levels for that reach.

1 Introduction

1.1 Background

In 1992, the Tunawaea Landslide introduced a large volume of bed material into the Waipa River, which is the largest tributary of the Waikato River (Figure 1-1). The transfer of this material along the Waipa channel has caused a number of channel management issues, and WRC has commissioned NIWA to carry out a morphological modelling investigation to predict the timing and magnitude of future bed level change along the Waipa channel as far downstream as Otorohanga to identify potential future channel management problems. This will help WRC to plan effective river management in response to these adjustments.

Figure 1-1: Map showing the location of the Waipa River and Tunawaea confluence upstream of Otorohanga. Note the location of the Otewa, Otorohanga and Whatawhata flow and suspended sediment monitoring stations.

1.2 The Waipa morphological modelling project

The Waipa morphological modelling project has been conducted in three phases in order spread the work and the cost of the work over a number of financial years. Two phases of work have been completed already and the results provided to WRC in two Client reports (Hoyle and Bind, 2013; Hoyle at al., 2014). Some of the information presented in those reports is repeated in this report such that this report can stand alone.

Phase 1 involved the collection of survey data in the Waipa River. This phase was completed in November 2013 and is described in the Hoyle and Bind (2013) report. Parts of the upper Waipa River had been surveyed previously but the most recent survey was in 2007/2008 and did not cover the full reach of interest to this study. The survey data collected in Phase 1 of this study provides the underlying topography for the Waipa River morphodynamic model and are described in more detail later in this report.

Phase 2 involved collection of surface and sub-surface bed material grain size distribution data in the Waipa and Tunawaea Streams, as well as additional survey data from the Tunawaea Stream. While in the field we also surveyed flood height pegs left by WRC staff to aid model calibration. This Phase of work also included the development of a preliminary (draft) morphological model. This phase was completed in August 2014 and is described in the Hoyle et al. (2014) report.

Phase 3 is the topic of this report and broadly covers the following three tasks:

Task 1: Analysis and data processing for model input, calibration and validation

- analysis of historical aerial photographs
- analysis of video collected by helicopter
- analysis of historical cross sections
- analysis of previous reports on the Tunawaea Landslide
- Summary of observed changes in the Waipa River in the period following the Tunawaea Landslide
- preparation of input files for the model; including starting topography and bed material layers, and flow and sediment input data

Task 2: Modelling

- hydraulic model calibration run
- bed sediment calibration run (1990 – 2014) ensuring the model can reproduce observed changes following the landslide
- a full run into the future (1990 - 2105), assessing future river adjustment as the Tunawaea material continues downstream
- a full run into the future (1990 – 2105) with no Tunawaea Landslide input, to be compared with the previous run in order to isolate the effects of the landslide.

Task 3: Reporting

- a description of the model (including its capabilities, data inputs, and calibration)
- details of modelled scenarios and interpretation of results
- conclusions and recommended mitigation measures if required.

1.3 The Tunawaea Landslide

The Tunawaea Landslide and the short term changes in the Tunawaea Stream and its confluence with the Waipa River are described in a series of papers in the Proceedings of the IPENZ Conference in Hamilton 5-9 February 1993 (Riley et al., 1993; Parkin et al. 1993; Jennings et al., 1993). The Tunawaea Landslide occurred on 18 August 1991 following heavy rainfall. The landslide involved an initial rockslide on the left bank of the Tunawaea Stream approximately 700 m upstream of the Waipa confluence. This was shortly followed by a further soil and rockslide immediately upstream of the initial slide on the left bank. The total volume of slide material was estimated at 4 million m^3. This landslide material formed a dam on the Tunawaea Stream which had a height of 50m above river bed on the upstream side and 70m on the downstream side. The dam gradually filled with water over the following month, forming a 900,000 m^3 lake upstream. Leakage through the landslide dam increased with water depth, but the dam did not fail until 22 July 1992, when heavy rain brought rivers up to about a 2 year return period flood. The landslide dam is believed to have overtopped when inflows exceeded leakage capacity (Riley et al., 1993).

The dam breach flood wave was estimated to have a peak flow of 250 m^3/s dissipating downstream to a recorded peak of 164 m^3/s at the Otewa gauge (Parkin et al. 1993). To place this in context, Parkin et al. (1993) report that a 100 year flood event at Otewa is estimated at 233 m^3/s and 175 m^3/s at Toa Bridge. While the flood wave dissipated downstream, its effects would have been particularly extreme in the upper parts of the study reach, where the valley is still reasonably confined.

Riley et al. (1993) describe three phases of landslide dam failure:

- Phase 1 – The initial breach, which occurred rapidly over 24 hours (Day 1) releasing a surge of water of about 250 m^3/s peak flow.
- Phase 2 – Widening and deepening of the breach and gravel deposition, occurring over the following week (Day 2 to Day 8).
- Phase 3 – Erosion of dam remnant and gravel deposits, occurring over the following five weeks (Day 9 to Day 44).

Further details of these phases of landslide erosion and the subsequent changes down the Waipa River following the Tunawaea Landslide are described in detail later in this report, as they are used to calibrate and validate the morphological model and to provide a broader picture of predicted river adjustment. However, in summary, the slug of bed material generated by the Tunawaea Landslide caused the Tunawaea/Waipa confluence to temporarily aggrade causing bed material supplied by the upper Waipa to back up behind the Tunawaea Landslide material. The reach immediately downstream of the Tunawaea confluence comprises a gorge of large (~ 1.5 m diameter) ignimbrite boulders, and these boulders were buried by the Tunawaea slug as it moved through this reach. Downstream of the ignimbrite gorge is a reach bordered on its right bank by a 16 m high terrace of

Taupo Pumice material (deposited by the Taupo eruption that occurred in 186 AD). In the period since the Tunawaea Landslide the aggrading riverbed allowed floods to undercut these terraces, eroding them back ~ 15-20 m, releasing an estimated 192,000-256,000 m^3 of additional sediment into the Waipa. As the Tunawaea slip material and eroded terrace material work their way down the Waipa, the bed is locally raised, exacerbating bank erosion and inducing overbank flooding. This has resulted in losses of native trees along the banks and ongoing maintenance is required, removing trees and debris along the river to help with flood control. Landowners downstream of Otorohanga indicated during a field visit that some material from the Tunawaea Landslide may have arrived in this reach of the river, saying that the material is welcomed as it has helped restore bed levels where there has been a trend of degradation.

1.4 History of channel works

Changes in the Waipa River over the period since the Tunawaea Landslide will not only be due to the large sediment input from the Tunawaea Landslide, but will also be influenced by human interventions in the channel over recent decades. For the purposes of this study NIWA requested information on the location, nature and timing of channel maintenance works; the location, timing and volumes of gravel extracted from the Waipa; information on the Otorohanga weir; and any other relevant engineering/channel management reports, as all of these activities are key potential morphological drivers over the multi-decadal scale and need to be considered when interpreting the modelled river behaviour during the calibration/historical phase of the modelling. Unfortunately very little information was available in this regard so, where required, we have inferred what we can from the aerial photographs and gathered anecdotal information. In summary we understand that:

- There was a large flood in 1958.
- Following the 1958 flood, channel control works were carried out downstream of Otorohanga, involving channel straightening.
- The channel straightening lead to incision and subsequently the weir was constructed upstream of Otorohanga to control headward erosion. The weir also services water supply to Otorohanga.
- A few ‘cuts’ (channel straightening) were carried out upstream of Otorohanga.
- The District Council carried out lots of gravel extraction for many years between Otorohanga and Toa Bridge prior to the Tunawaea slip, but take less now.
- WRC spent approximately $1 million on restoration in the early 2000s, mostly in 2004/2005 and mostly involving planting in the 6-10 km downstream of the Tunawaea confluence aimed at stabilising the Tunawaea sediment and preventing it moving downstream to Toa Bridge.

1.5 Report structure

In this report we start by introducing the keys locations in the study reach that we refer to throughout the report (Section 0). We then provide a detailed methodology of the various steps taken to paint the picture of river adjustment in the Waipa channel since the Tunawaea Landslide event and the various steps taken in the modelling process (Section 3). The results from this study (Section 4) are presented in four parts:

1. results from the analysis of the historic aerial photographs,
2. results from the analysis of historic cross section surveys,
3. results from the model calibration, and
4. results from modelling of predicted future river adjustment.

In the discussion (Section 5) we provide our interpretation of what the various results mean, and in the conclusion (Section 6) we provide a summary of river changes to date and what is expected into the future. We also provide recommendations as to how WRC might use this information and future work they may wish to carry out.

2 Modelled reach

The reach of interest along the upper Waipa River runs from approximately 200 m upstream of the Tunawaea confluence down to the State Highway Bridge at Otorohanga. A number of key locations and sub-reaches are referred to throughout this report, and results are often related to either river distance (measured downstream from the top of the study reach) or cross section location. Figure 2-1 shows these key locations relative to river distance on the 1:50000 topographic map. Figure 2-2 maps the key sub-reaches onto the 2012 aerial photograph. Figure 2-3 locates existing cross sections (previously surveyed for WRC and re-surveyed by NIWA for this study) and new cross-sections (surveyed for the first time by NIWA for this study).

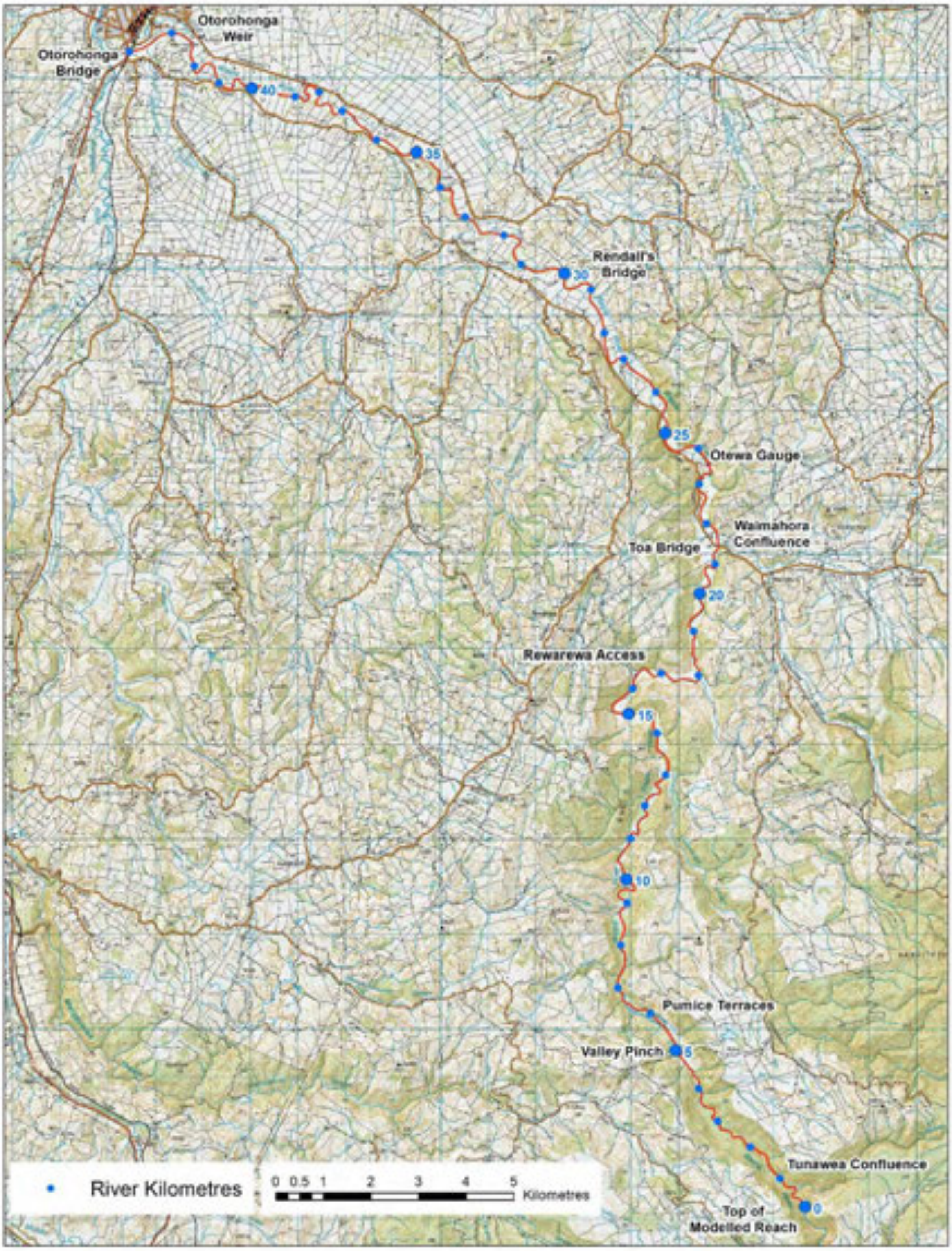


Figure 2-1: Map of the modelled reach of the upper Waipa River identifying key locations, relative to river distance, overlaid on the 1:50000 topographic map. River distance is marked every kilometre with a blue dot, and numbered every 5 km starting from the upstream end of the study reach.

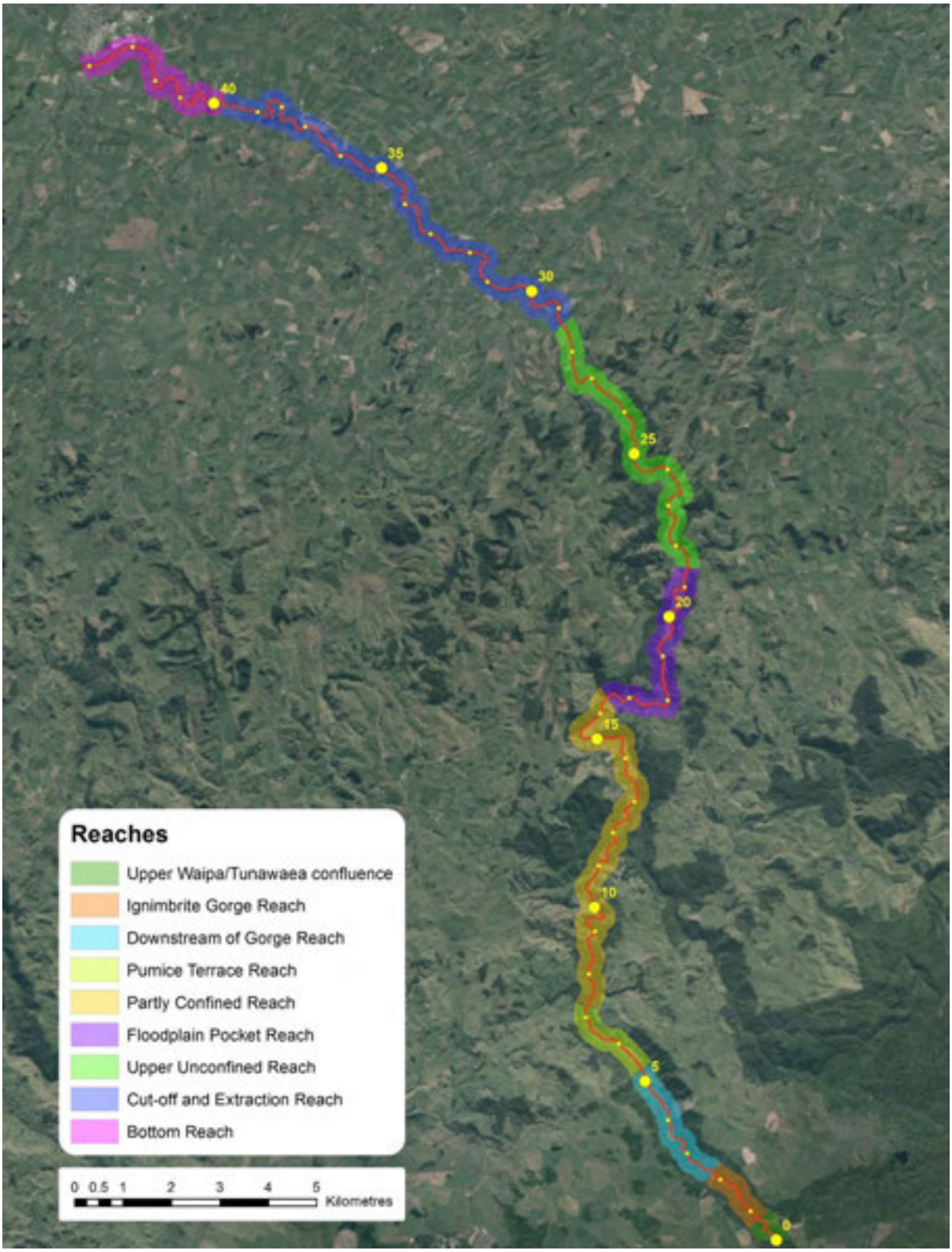


Figure 2-2: Map showing the modelled reach of the upper Waipa River, identifying key sub-reaches relative to river distance. River distance is marked every kilometre with a yellow dot, and numbered every 5 km starting from the upstream end of the study reach.

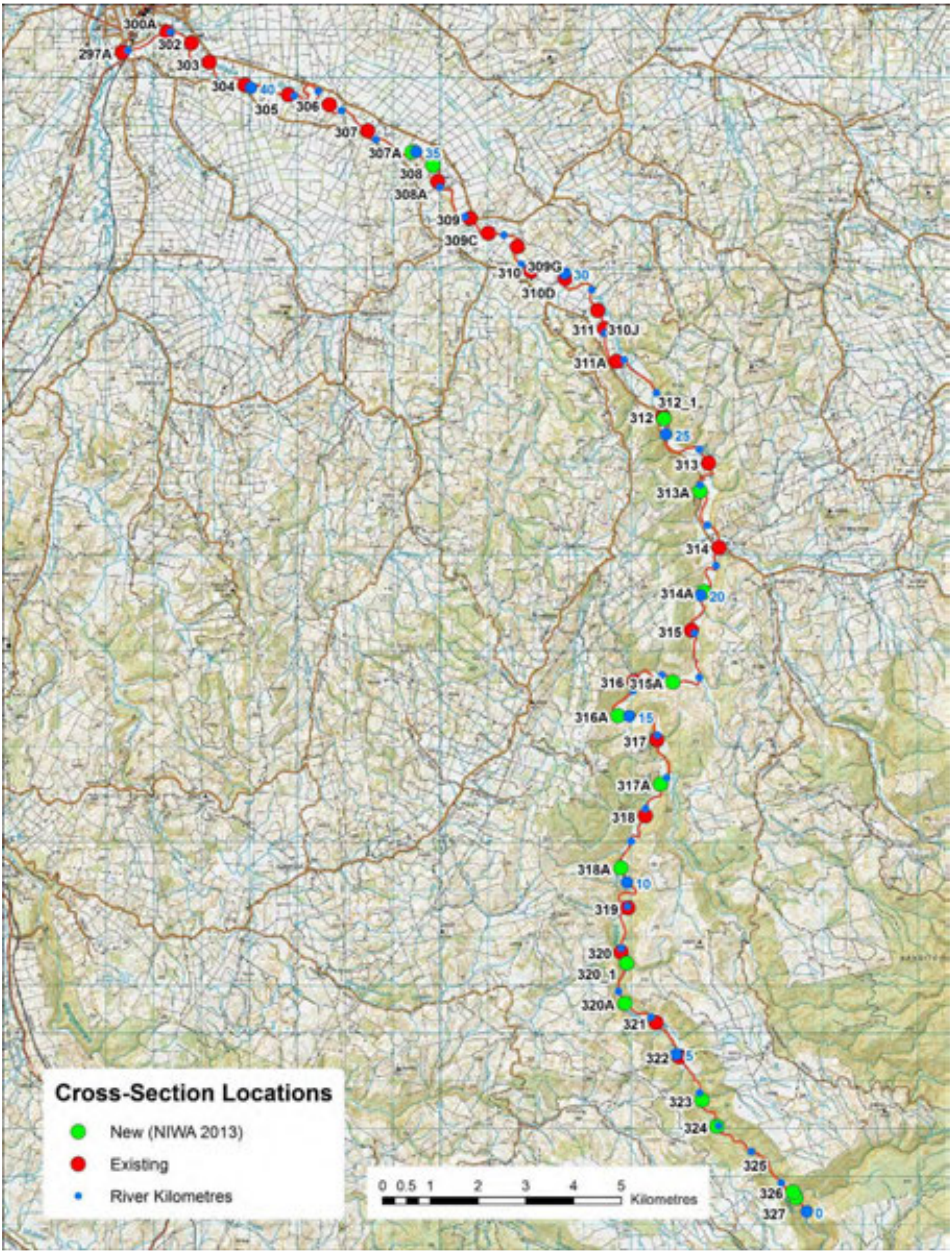


Figure 2-3: Map of the modelled reach of the upper Waipa River showing the location of new and existing cross sections relative to river distance, overlaid on the 1:50000 topographic map. Note: both new and existing cross sections were surveyed by NIWA for this study, but cross sections changes could only be assessed where there were existing cross sections.

3 Methodology

A morphological model requires data to initiate and drive it through time as well as data to validate its output. Also, the model may need some adjustment (or calibration) of its input files or parameters to align its output with historical observations. A key preliminary exercise is to develop a conceptual model of events and how the river has adjusted. The following sections describe the various steps taken to paint the picture of river adjustment in the Waipa channel since the Tunawaea Landslide event and the various steps taken in the modelling.

3.1 Timeline of events and data availability

To paint a picture of how the Waipa River has adjusted following the Tunawaea Landslide we first needed to assess what data are available that describes the upper Waipa prior to landslide and at various points in time following the landslide. The timing of the data also need to be placed in the context of other events (such as floods) that have occurred in the catchment. To do this we constructed a timeline (Table 3-1). Not all of these data are used in this study but the timeline helps to identify what might be useful.

Table 3-1: Timeline of data collection and key events in the upper Waipa River. Note the exact timing of the Otorohanga weir, channel straightening and gravel extraction campaigns are unknown.

Timing	Data/Event
1958	Big flood (discharge unknown) and first available cross sections – covering cross sections 302 to 309
1959	Otorohanga stopbank system built
1960 ?	Channel straightening upstream and downstream of Otorohanga
Aug 1962 & Jan 1971	Cross section at weir
16 June 1978	Cross sections – covering cross sections 303 to 309
May 1979	Cross sections between Toa Bridge and Rendall's Bridge – 3 in total
22 May 1981	Start of flow record at Waipa at Otorohanga
27 January 1983	Aerial photographs – Black and white at 1:50000 flown by NZAM.
22 May 1985	Start of flow record at Waipa at Otewa
November 1985	Cross sections below Toa Br 309-310H
September 1986	Cross sections below Toa Br 309-311A
November 1987	Cross sections below Toa Br 309-311A
December 1989	Cross sections between weir and Toa Br – 9 in total
23 March 1990	Cross sections between weir and Toa Br – 4 in total
August 1991	Tunawaea Landslide (probably occurred on 9-10th as that coincides with a flood event)
22 July 1992	Tunawaea Landslide dam failure
5-9 February 1993	Published descriptions of landslide dam failure and short term changes in Tunawaea and Waipa (Riley et al., 1993; Parkin et al. 1993; Jennings et al., 1993)
1 July 1993	Aerial photographs – Black and white at 1:27500. Have a gap at the Pumice terrace reach
9-10 July 1998	Second largest flood on record for Waipa at Otewa (325 m^3/s) and Waipa at Otorohanga (419 m^3/s)
1999	Cross sections between weir and Toa Br – 13 in total
2 October 2000	Third largest flood on record at Waipa at Otewa (258 m^3/s)
Summer 2001/2002	Aerial photographs - colour digital ortho photography
2002	Cross section at 314A
7 July 2002	Third largest flood on record at Waipa at Otorohanga (352 m^3/s)
29/02/2004	Largest flood on record for Waipa at Otewa (442 m^3/s) and Waipa at Otorohanga (646 m^3/s)
Dec 2007-Jan 2008	Cross sections between pumice terraces and weir – DML survey
2007	Aerial photographs - colour digital ortho photography
2007/2008	LiDAR – contours only
November 2010	Helicopter video –covers reach from Rewarewa access to Tunawaea
2010/2011	LiDAR – contours only
3 February 2011	Survey data at weir
April- May 2012	Aerial photographs - colour digital ortho photography
2012/2013	LiDAR – contours only
June-October 2013	Cross sections from u/s Tunawaea to Otorohanga – full reach NIWA survey
October 2013	Surface bed material grain size data collection (Wolman pebble counts) – NIWA field work

We assume these repeated cross sections in a specific reach are related to gravel extraction

3.2 Analysis of historic cross sections

Historical cross section data are patchy in space and time throughout the study reach (Appendix A). Survey data are available for 1958, August 1962, December 1963, January 1971, June/July 1978, May 1979, November 1985, September 1986, November 1987, December 1989, March 1990, 1999, 2002, 2007/2008 and 2013. However, most of these surveys are of very limited spatial extent, and are therefore of limited use to this study. The only survey that covers the full reach of interest is that carried out by NIWA in 2013 (Hoyle and Bind, 2013). The preceding 2007/2008 survey, carried out by DML, covers the reach from Otorohanga to approximately 1 km upstream of the Pumice Terraces. No other surveys extend upstream of Toa Bridge, and many only cover a few cross sections.

A brief comparison of the 2007/2008 DML survey data with NIWA's 2013 survey data was provided by Hoyle and Bind (2013). A more detailed comparison of all available cross section survey data has been carried out as part of this study. This involved compiling all available cross section data in one spreadsheet and overlaying the surveys from various years for an initial visual assessment. Offsets were adjusted to line up the river channel and bank positions. The visual comparison allowed a qualitative analysis of the development of the bed levels (and river banks) over the period covered by existing survey data, revealing times of aggradation and erosion.

To compare observed trends in river behaviour (as shown by the historic cross sections and aerial photographs) with model outputs, a quantitative measure of river adjustment had to be developed to allow a calibration of the model. A usable indicator is the mean bed level within the active river channel. Based on the latest survey (NIWA, 2013), a point just inside the top of the river bank was selected on each bank and mean elevations were calculated between these points for all surveys at each cross section. Differences between these mean bed levels from survey to survey could then be used to indicate trends in aggradation or degradation at each cross section over time. 1978-79, 1985-87, and 1989-90 surveys were combined into groups to allow plotting/analysis over longer reaches than would have been possible with the individual surveys.

3.3 Analysis of historic aerial photography

WRC supplied NIWA with aerial photographs of the study reach for 1983, 1993, 2002, 2007 and 2012. The 1983 and 1993 photographs are black and white, and the other photographs are colour and of higher resolution. The 1993, 2007 and 2012 photographs were made available under the Creative Commons Attribution 3.0 New Zealand Licence courtesy of the Waikato Regional Aerial Photography Service (WRAPS). Photographs from 2010 and 2011 are also available for some locations on Google Earth.

Each aerial photograph was georeferenced so that all photographs could be overlaid in ArcGIS, along with river distances and cross section locations. Analysis of river adjustment involved noting changes between consecutive photographs in features such as: channel width, exposed gravel bar area, planform pattern (e.g. meandering versus braiding low flow channel), vegetation cover on bars, and channel maintenance works (in particular willow planting).

3.4 Analysis of landslide and Tunawaea Stream changes

Detailed descriptions, figures and photographs of the Tunawaea Landslide are provided in Riley et al. (1993), Parkin et al. (1993) and Jennings et al. (1993). The information provided by these papers was compared with our own observations, photographs and survey data collected in the Tunawaea Stream and around the confluence with the Waipa in July 2014 in order to assess the rate at which the Tunawaea slip material has entered the Waipa River. This information was used to develop the Tunawaea sediment input for the Waipa morphological model.

3.5 Morphological modelling approach

The morphological modelling involved:

1. Selecting an appropriate model for assessing changes in the Waipa due to the Tunawaea Landslide.
2. Model build – processing survey and monitoring data to compile the model and all the inputs required to simulate the effects of the landslide.
3. Hydraulic calibration – simulation of flows with surveyed water surface elevations. Adjustment of roughness as required to achieve a close match between modelled and observed water levels.
4. Sediment/morphology calibration – simulation of channel bed level change and bed-material size grading over the period from 1/1/1990 to 1/1/2015 and adjustment of model inputs and parameters to match observations of morphological change during this period.
5. Simulation of future changes.
6. Interpretation of results. With any morphological modelling it is necessary to interpret the results within the context of:
    - the magnitude and sources of residual error in the model following sediment/morphology calibration; and
    - wider observations and understanding of the river processes and ongoing changes, including understanding gained during the data collection and processing done to develop the model.

3.6 The GRATE model

The modelling software GRATE (Walsh, 2010) was selected for several reasons:

- GRATE is **one-dimensional**: 1D morphological models such as GRATE are much simpler than 2D or 3D models allowing them to simulate long river reaches for long periods of time. It would not be practical to simulate the length of Waipa channel and time period required using a 2D or 3D model. Also the high resolution of input data required to develop a 2D or 3D model would not have been practical to collect in the Waipa River.
- GRATE allows the use of **quasi-steady hydraulics**: This is a further simplification allowing rapid simulation of long time periods by permitting a much longer time step.
- GRATE incorporates **multiple size fractions**: This allows GRATE to simulate the bed composition changes resulting from the Tunawaea Landslide and the feedback effects on transport rates and bed levels (including the development of bed-surface armour).

- GRATE accounts for **abrasion**: Abrasion reduces the size of transported particles and generates silt which can be transported as washload. Angular, freshly eroded material, such as from the Tunawaea Landslide, may be more vulnerable to abrasion and hence it is important to be able to include this process in the model.

3.7 Data processing and analysis for model input files

In order to run the GRATE model a series of input files are required. The key requirements are to set the starting topography (cross section input file), starting grain size distribution of the surface and sub-surface bed material layers (sediment input file), the flow time series for water entering the model (flow time series input files), and the bedload input time series for bedload entering the model. The methods used to develop these files are described below. Various other parameters need to be set at the start, such as rates of abrasion and form roughness, and, like the input files, these may need to be adjusted during the calibration process (Sections 3.8.1 and 3.8.2).

3.7.1 Cross sections

The cross-sections used in the model were based on the 2013 NIWA cross-section survey (Hoyle and Bind, 2013). Cross-section processing to prepare them for the model included:

- **Extending cross-sections and gap filling:** Where required, additional data points were inserted to extend or fill gaps in cross-sections based on notes and photographs collected during the survey. For example, extending banks or filling in gaps where it was too deep to wade.

- **Active channel identification:** Markers where inserted at the locations of the left and right bank limits of the active channel. The active channel limits were identified based on cross-section shape, and presence/absence of vegetation as observed during the survey and from aerial photographs.

- **Additional cross-sections:** In some locations it was necessary to artificially generate additional cross-sections to better represent changes in channel slope or active width. Additional cross-sections were generated for: the Ignimbrite Gorge reach (where it was not possible to survey), at the Otorohanga Weir (to accurately represent the weir crest and the sharp change in bed level downstream of it), and in the short constricted reach upstream of the pumice terraces (to better represent the slope changes through this reach). Cross-sections were created by replicating and adjusting similar surveyed cross-sections based on aerial photographs and surveyed water level profile except for the Otorohanga Weir which was based on a survey conducted by DML (DML 2011).

- **Bedrock elevation:** GRATE includes the capability to set a bedrock elevation below which the bed cannot erode. In the Waipa model this functionality was used in the gorge reaches and at the weir. At these locations a bedrock elevation was specified at, or slightly below, the current surveyed minimum bed level.

- **Interpolation:** Cross-section spacing was reduced by interpolation to improve model hydraulic stability and accuracy. The final cross-section spacing ranged from 150m to 15m and was set based on water level slope, with closer spacing required in area of steeper water slopes, such as in the upper part of the model, particularly the ignimbrite gorge, and around the Otorohanga Weir.

- **Bed level adjustments:** For simulations of historic bed level change it was necessary to first reset the model bed levels to their historic level at the start of the simulation. For cross-sections for which a survey was available from around the start time of the model, the difference between the mean bed level of the historic survey and the 2013 survey was applied. For cross-sections where this was not available, bed level changes were estimated based on anecdotal information and aerial photographs and then adjusted during calibration.

Summary data on the final cross-sections used in the model is provided in Appendix B.

3.7.2 Flow time series

Flow data from the Waipa at Otewa flow gauge were used as the basis for flows in the model. In order to distribute flow into the model correctly tributary catchments were identified using NIWA's River Environment Classification (REC2) catchment dataset as shown in Figure 3-1. Flow recorded at the Otewa gauge was distributed between the different sub-catchments using an area weighting approach and put into the model at defined locations as shown in Table 3-2. As the model is running in quasi-steady mode it does not account for travel time along the river channel so no-time lagging of flow inputs was required.

The area weighting approach was modified for 22 July 1992 in order to account for release of water from the Tunawaea Landslide dam during its failure. For this day the flow record was manually separated into an assumed 'natural' flow and a landslide dam break flow. The 'natural' flow was then area weighted, and the whole of the landslide flow assigned to the Tunawaea Stream catchment.

Otewa flow data are available from 22 May 1981, giving 33 complete years of data. For simulations of future change this flow time series was looped on the assumption that future flows would be similar to recorded historic flows.

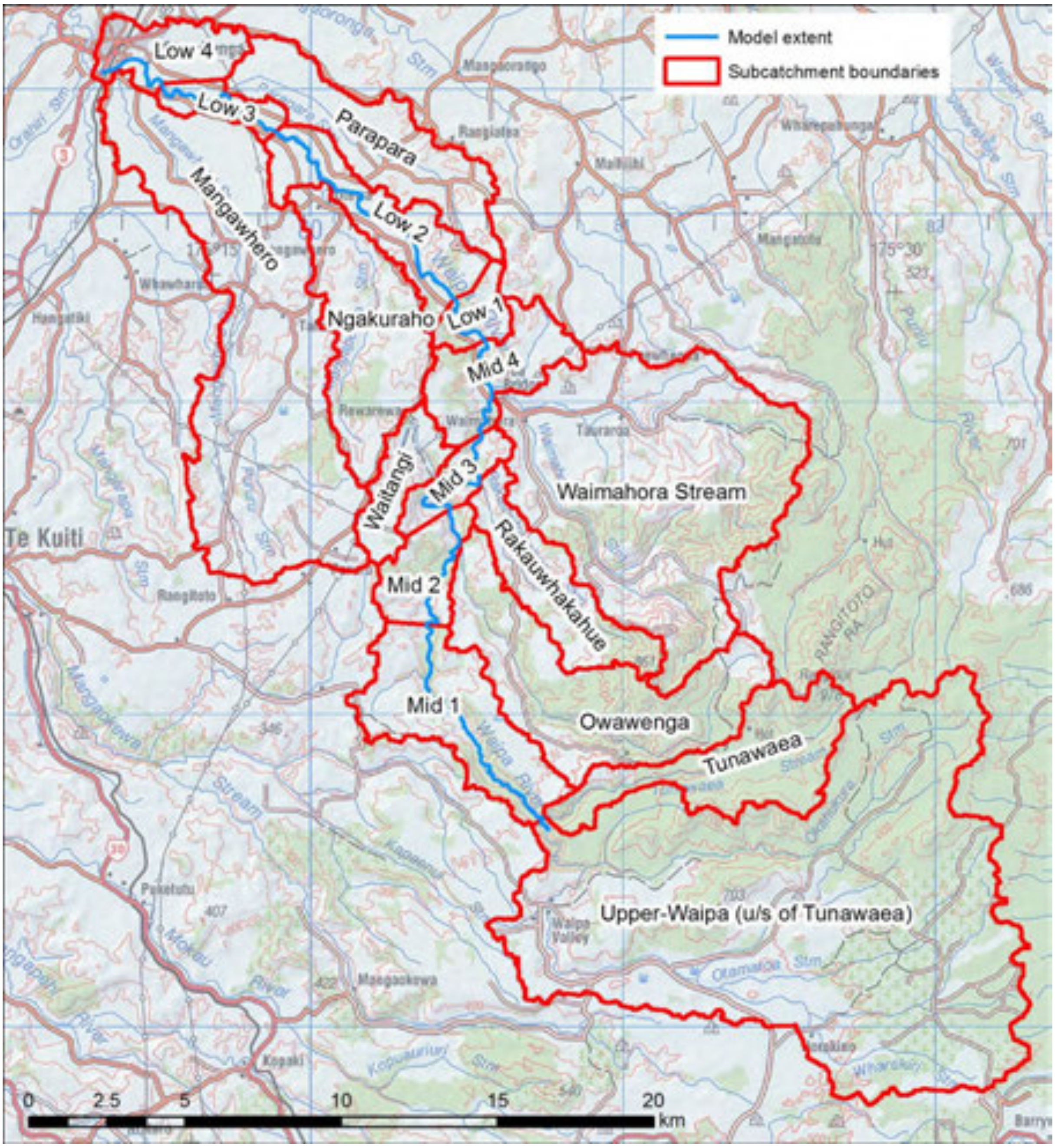


Figure 3-1: Model sub-catchment locations.

Table 3-2: Sub-catchment flow inputs to model.

Sub-catchment	Area (ha)	% of Otewa	Location flow added to model (km)
Upper Waipa (u/s of Tunawaea)	13,383	42.0%	0.317
Tunawaea Stream	1,993	6.2%	0.661
Mid 1	2,035	6.4%	6.691
Owawenga Stream	3,268	10.2%	12.810
Mid 2	762	2.4%	
Waitangi Stream	729	2.3%	17.302
Mid 3	504	1.6%	
Rakauwhakahue Stream	1,410	4.4%	
Waimahora Stream	6,638	20.8%	21.434
Mid 4	1,166	3.7%	
Low 1	421	1.3%	
Ngakuraho Stream	2,271	7.1%	32.887
Low 2	1,453	4.6%	
Parapara Stream	2,041	6.4%	39.128
Low 3	392	1.2%	
Mangawhero Stream	6,444	20.2%	Not added to model
Low 4	867	2.7%	

3.7.3 Bed-material and sediment inflow size composition

Surface and sub-surface bed material grain size distribution data were collected at various locations in the Waipa River and in the Tunawaea and Waimahora Streams in Phase 2 of this study. Hoyle et al. (2014) give a detailed description of the methods used in collecting these data. The grain size distributions for the surface and sub-surface bed material at the sampling sites are presented in Figure 3-2 and Figure 3-3 respectively. These data were used to assign an appropriate initial surface and sub-surface grain size distribution to each cross section in the model. They are also used to establish the size distribution of the sediment feeds entering the Waipa at the top of the model reach and entering from the Tunawaea and Waimahora tributaries.

The grain size distribution of the sediment feeds were assigned based on the nearest subsurface sample, i.e. the upper Waipa feed was based on the subsurface sample taken in the Waipa upstream of the Tunawaea confluence, the Tunawaea feed was initially based on the subsurface sample taken in the Tunawaea, and the Waimahora feed was based on the subsurface sample taken in the Waimahora.

Originally it was intended to include a lateral feed of sediment representing pumice terrace material entering the Waipa river system due to bank erosion. However, the samples of pumice terrace material showed that it was almost entirely composed of sand and silt sized grains (Figure 3-3). This fine grain size coupled with its low density makes it likely that much of the material eroded from the pumice terraces was transported as washload and had little effect on the bed levels. This hypothesis is supported by the fact that very little identifiable pumice was found in any of the downstream sediment samples. Based on these observations it was decided not to include a pumice sediment feed in the model.

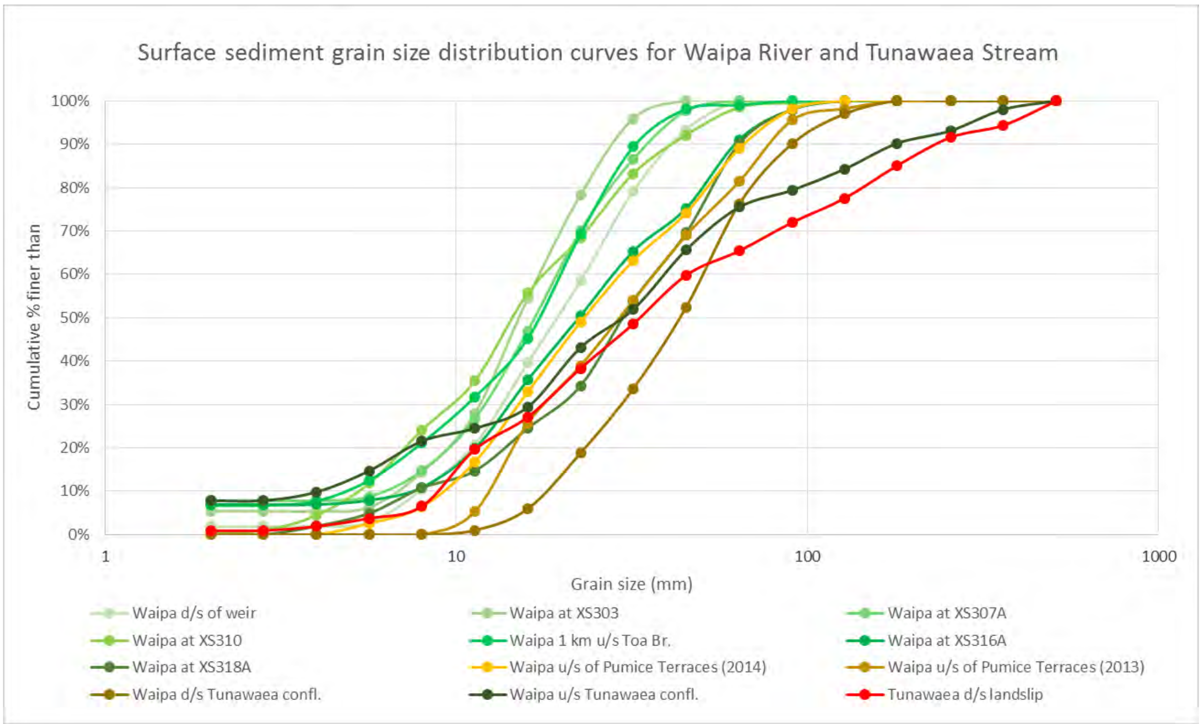


Figure 3-2: Surface sediment grain size distribution curves for Waipa River and Tunawaea Stream.

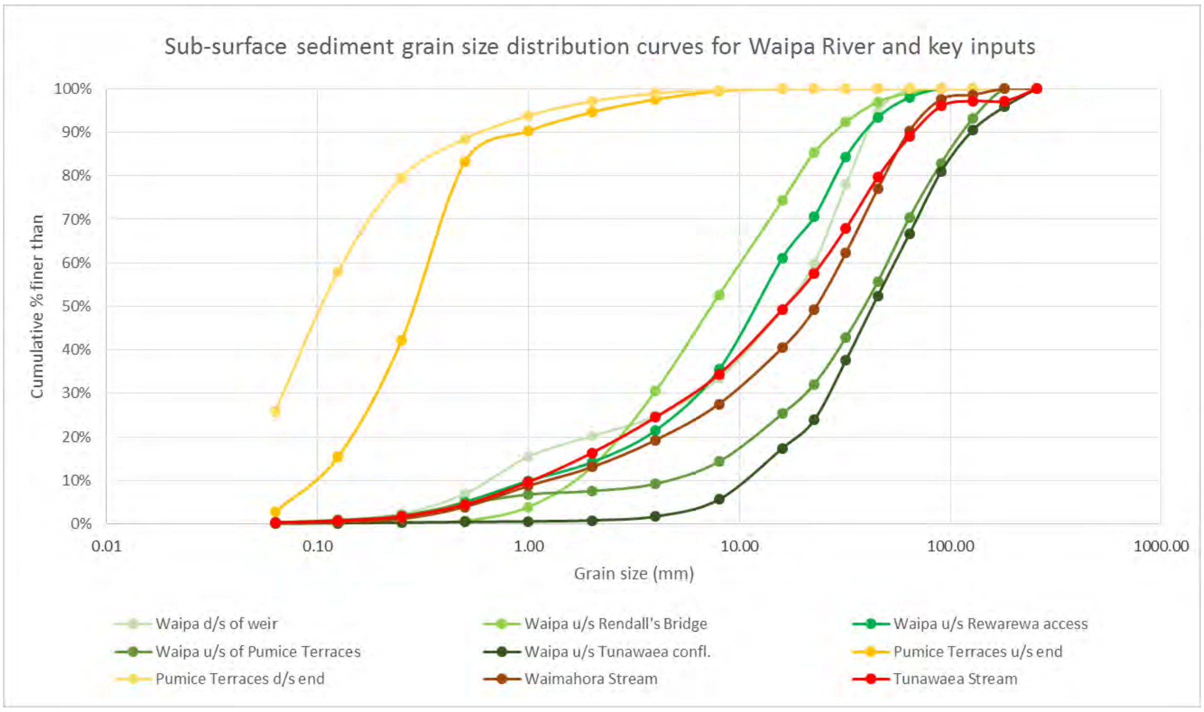


Figure 3-3: Sub-surface grain size distribution curves for Waipa River, Tunawaea Stream, Waimahora Stream and Taupo Pumice terraces.

To assign a grainsize distribution to the surface and subsurface at each cross section, the approach we used was to examine the long profile of the Waipa River and split it into sections based on changes in gradient (Figure 3-4). The cross sections falling within each of these sections were then assigned an initial surface and subsurface grain size profile based on the average of the sediment distributions sampled within that section. For example, the cross sections falling between river distances 7 and 25 km were assigned a surface grain size distribution based on the average of the three samples taken in that section of river (i.e. Waipa 1km u/s Toa Br, Waipa at 316A and Waipa at 318A) and the sub-surface grain size distribution was assigned the distribution sampled upstream of Rewarewa access, as this was the only sub-surface sampling site in the Waipa River in that section of river.

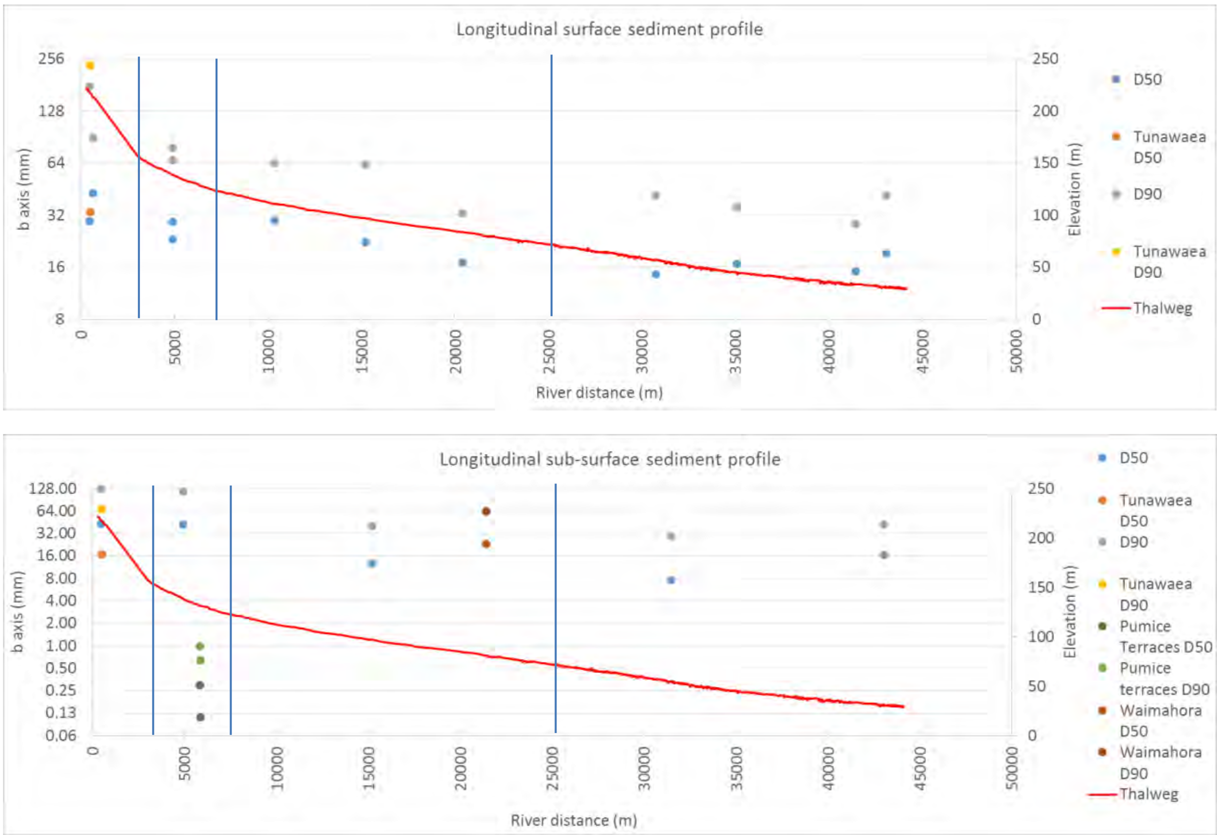


Figure 3-4: Surface (top) and sub-surface (bottom) sediment sampling sites overlaid on the long profile. The long profile is split into sections at around 4000, 7000 and 25000 m based on changes in long profile gradient.

The reaches over which the grainsize profiles were averaged were adjusted during morphological calibration. The 11 final size distributions used in the model are tabulated in Appendix C and the surface and subsurface compositions assigned to each cross-section are tabulated in Appendix B.

3.7.4 Bedload feed rate

There are no previous estimates of bedload transport rate in the Waipa or any of its tributaries on which to base the model bedload feed rate. An initial estimate of bedload transport was made by running the model with sediment transport turned on but no morphological updating. In this way the model calculated equilibrium transport rate at each cross-section without changing bed elevations or compositions. The model results were analysed to calculate a spatially averaged bedload rating for the central reach of the model from 22 to 32 km. This rating was applied to the Otewa flow record to derive a timeseries of bedload feed. The timeseries was then catchment area weighted to derive initial estimates of sediment feed rates for the Upper Waipa, Waimahora Stream and Tunawaea Stream (excluding landslide derived sediment).

In addition to the normal conditions bedload feed it was necessary to derive a timeseries for landslide derived sediment input into the Waipa from Tunawaea Stream. The assumptions used to derive this feed rate were:

- Additional landslide derived sediment feed commenced on 22 July 1992 when the landslide dam failed.
- Landslide derived bedload sediment delivery at any given point in time is proportional to Tunawaea flow at that time.
- The bedload rating coefficient linking Tunawaea flow and bedload sediment delivery exponentially decays over time.

These assumptions give the following equation for landslide derived bedload feed:

$$q_s = Q.R$$

Where q_s is landslide derived bedload feed at time t, Q is Tunawaea Stream flow at time t, and R is the rate coefficient exponentially reducing over time according to the equation:

$$R = 2^{-(t-t_0)/t_{1/2}}.R_0$$

Where t_0 is the time of dam failure, $t_{1/2}$ is the half-life of the exponentially decaying rate coefficient, and R_0 is the initial rate coefficient immediately after dam failure. The half-life was initially set at 1 year and the initial rate coefficient was adjusted so the total sediment supplied up to July 2014 equalled 250,000 m^3 (see Section 4.2.1 for the basis of this estimate).

3.7.5 Other model inputs

Other important model parameters set during model build include:

- **Form roughness.** In GRATE, total bed roughness at each cross-section is a combination of form roughness and grain roughness, where grain roughness is calculated as a function of surface grain size. Before setting an initial estimate of form roughness, grain roughness was calculated based on surface sediment size distribution (see Section 3.7.3) and total roughness was estimated based on river slope, grain size and mean flow (Hicks and Mason 1998). Form roughness was then estimated based on the difference between total and grain roughness. Form roughness was adjusted during calibration and the final values at each cross-section are shown in Appendix B.
- **Sediment layer setup.** GRATE stores information about bed sediment composition in several layers including the ‘active layer’, representing the bed surface, a number of ‘storage layers’, representing deposited material, and the ‘underlayer’, representing sub-surface material below the storage layers. Active layer thickness (constant) was set at 0.128 m, approximately equal to the largest grain size present in the river. Maximum storage layer thickness was set at 0.5m, with a maximum of 10 layers, to allow tracking of the build-up and re-working of landslide derived sediment deposits.

- **Non-equilibrium adaptation length.** The non-equilibrium adaptation length is a length scale used for smoothing sediment transport rates. For bedload transport it is generally taken as representative of the length scale of morphological features such as bars. The non-equilibrium adaptation length for the Waipa model was set at 200 m based on the typical bar length measured off aerial photography.

Other model input parameters and the basis for their selection are shown in Appendix D.

3.8 Model runs

3.8.1 Hydraulic model calibration

In order to collect data to inform hydraulic calibration peak flood levels were pegged following a small flood on 12 June 2014 (Russell Powell pers. comm.) and surveyed using RTK GPS by NIWA on 24 July (survey calibrated to left bank benchmark at cross-section 313). Survey data are given in Appendix E. The peak flow recorded at Otewa corresponding to the surveyed flood levels was 83.1 m^3/s.

To calibrate the model a constant flow of 83.1 m^3/s was simulated at Otewa (scaled and distributed between the various model inflows as shown in Figure 3-1and Table 3-2). A constant flow was simulated because the model uses simple quasi-steady hydraulics so the phasing of different sources to the hydrograph has no effect on peak levels. The model water level was compared with the observed peak water level and the form roughness adjusted to improve the fit between modelled and observed levels.

3.8.2 Morphology calibration

Morphology calibration involved simulating the period 1990 to 2014. The model predictions of bed level change were compared with observed bed level change based on the analysis of historic cross-sections (see Section 3.2 for details of the analysis of historic cross-sections), anecdotal information on river changes, and changes visible from aerial photography (aerial photography analysis described in Section 3.3). In addition the model surface and subsurface sediment composition in 2014 were compared with sampled bed surface composition data (Hoyle at al., 2014). Model parameters were then adjusted within the range of values appropriate in order to improve fit between the model and reality. This iterative calibration process provided valuable insight into the sensitivity of the model and the dominant processes controlling sediment transport in the modelled reach of the Waipa.

3.8.3 Future simulations

Following morphological calibration two simulations were performed for the period 1990 – 2105. The first simulation was identical to the morphological calibration, but extended into the future by repeating the available flow data. The second simulation was for the same period but did not include any landslide derived sediment. This simulation was carried out in order to be able to isolate the effects of the landslide to inform understanding of its effects and the potential future effects of another large landslide in the Tunawaea.

4 Results and Interpretation

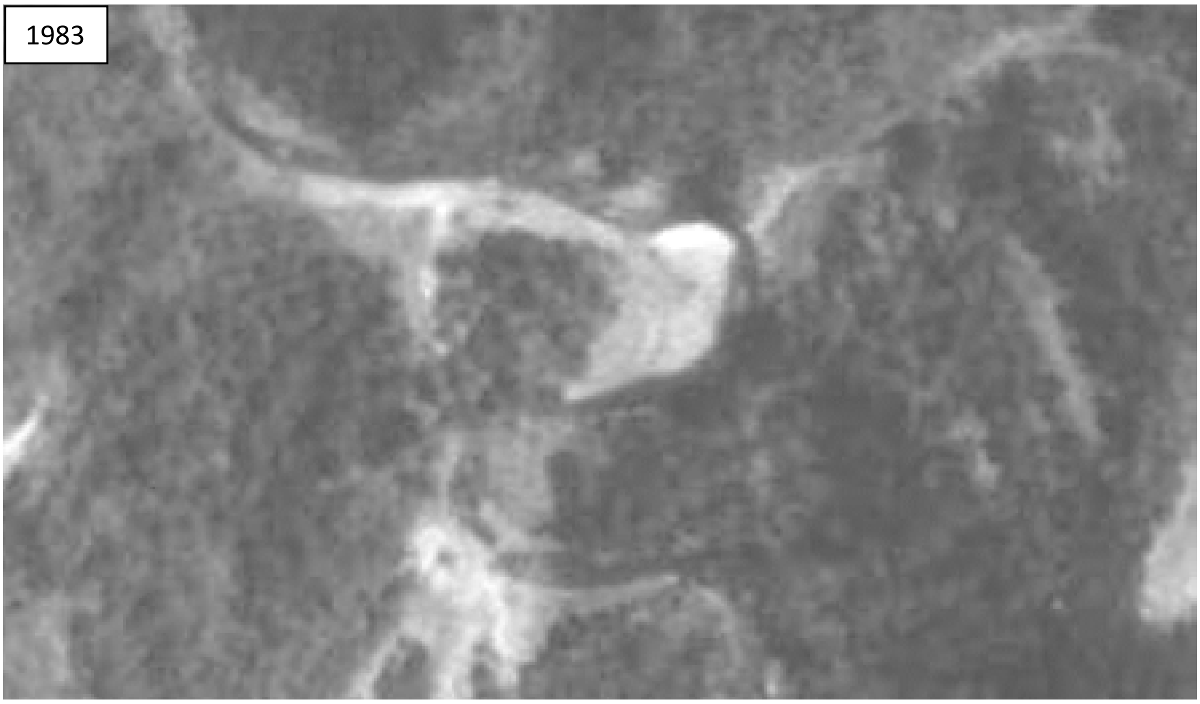
4.1 Analysis of historic photographs

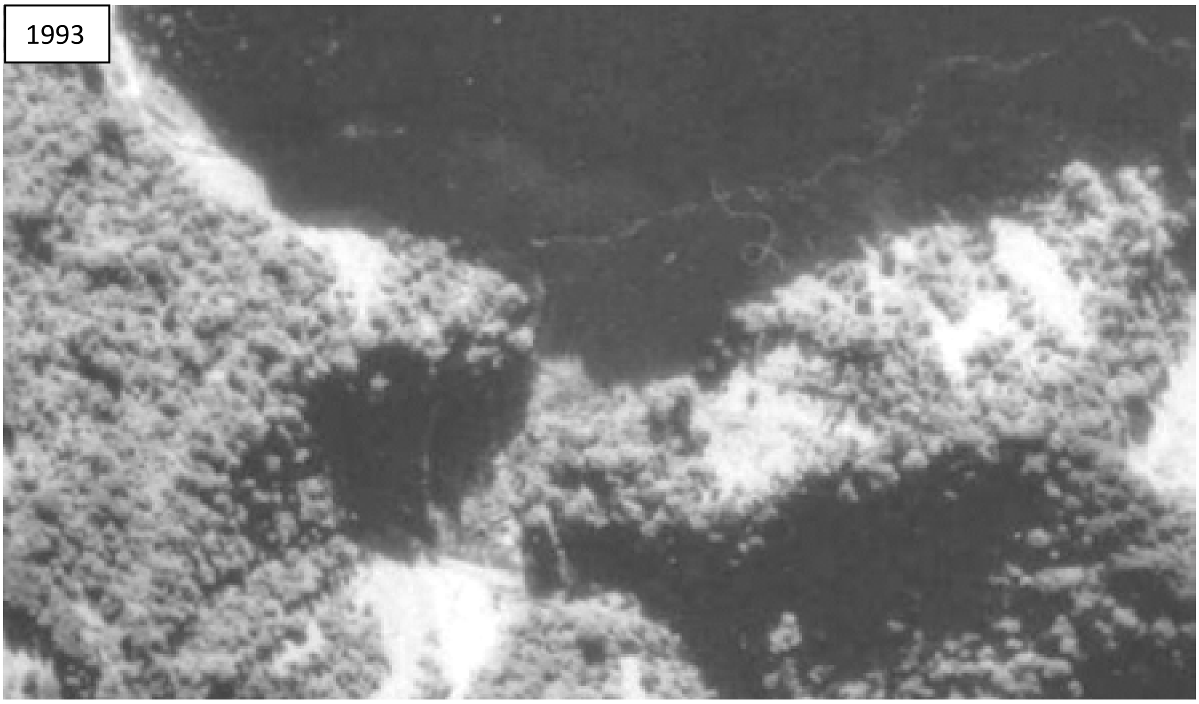
The observed changes in the Waipa River following the Tunawaea Landslide are described in this section by breaking the study reach into a series of sub-reaches (Figure 2-2). Example photographs are presented for each of these sub-reaches to demonstrate the changes observed. These photographs are of varying resolution and quality, and the flow rate sometimes appears to be different (e.g. the flow appears a little high and turbid in the 1993 aerials), but each set of photographs is presented at the same scale so that locations can be directly compared over time. The overall changes along the modelling reach are summarised in Section 4.3.

4.1.1 Upper Waipa and Tunawaea confluence reach

The upper Waipa and Tunawaea confluence area has, unsurprisingly, undergone large changes since the Tunawaea Landslide. Figure 4-1 presents a series of aerial photographs of this area. In 1983, prior to the landslide, the Waipa low flow channel sat hard against the right bank with a large (60 m wide) point bar on the left bank, opposite the confluence. In 1993, following the landslide, the Waipa low flow channel has been pushed hard against the left bank by a large fan of gravel extending from the Tunawaea. The 1993 aerial photograph is not particularly clear but a photograph presented by Riley et al. (1993) shows an oblique view of the confluence 44 days after the Tunawaea dam collapse (Figure 4-2) which clearly shows braided channels forming within the outwash fan. In the 1993 aerial photographs the Waipa upstream of the confluence appears little different to in 1983, indicating that not a lot of gravel has accumulated there. The situation at the confluence appears largely the same in 2002, with the Waipa channel still pushed hard against the left bank by the Tunawaea fan. Upstream of the confluence there are large (~40 m wide) bare gravel bars indicating that Waipa gravel is backing up due to the elevated bed level at the confluence. By 2007, the confluence is just starting to clear of Tunawaea gravel, the bars have started to revegetate, and the Tunawaea low flow channel is braiding across its gravel fan. By 2012, the Waipa has managed to clear much more of the gravel at the confluence, with the main low flow channel pushed back to the right at the confluence. There are still large bars of gravel present but these are generally perched above the low flow channel and are well vegetated.

Further evidence of change in the Tunawaea is presented in Figure 4-3, which shows a large kahikatea tree, located approximately 100 m upstream of the Waipa confluence (also indicated on the later aerial photographs in Figure 4-1) in 1992 and again in 2013. The 1992 photograph is from Riley et al. (1993) and they state that it was taken during ‘Phase 3’ following the Tunawaea Landslide dam collapse (see Section 1.2). Riley et al. (1993) estimate that the tree has already been exhumed by approximately 4 m (measured relative to the adjacent remnant gravel terrace) and was still buried by an estimated 10-15 m. The 2013 photograph was taken by NIWA staff and we estimate that the tree has now been exhumed by approximately 12 m, and is perhaps still buried by 2-5 m.


1983


1993


2002


2007

Figure 4-1: Aerial photographs showing changes in the upper Waipa/Tunawaea confluence sub reach. Note flow in the Waipa is from bottom to top, with the Tunawaea joining on the true right bank.

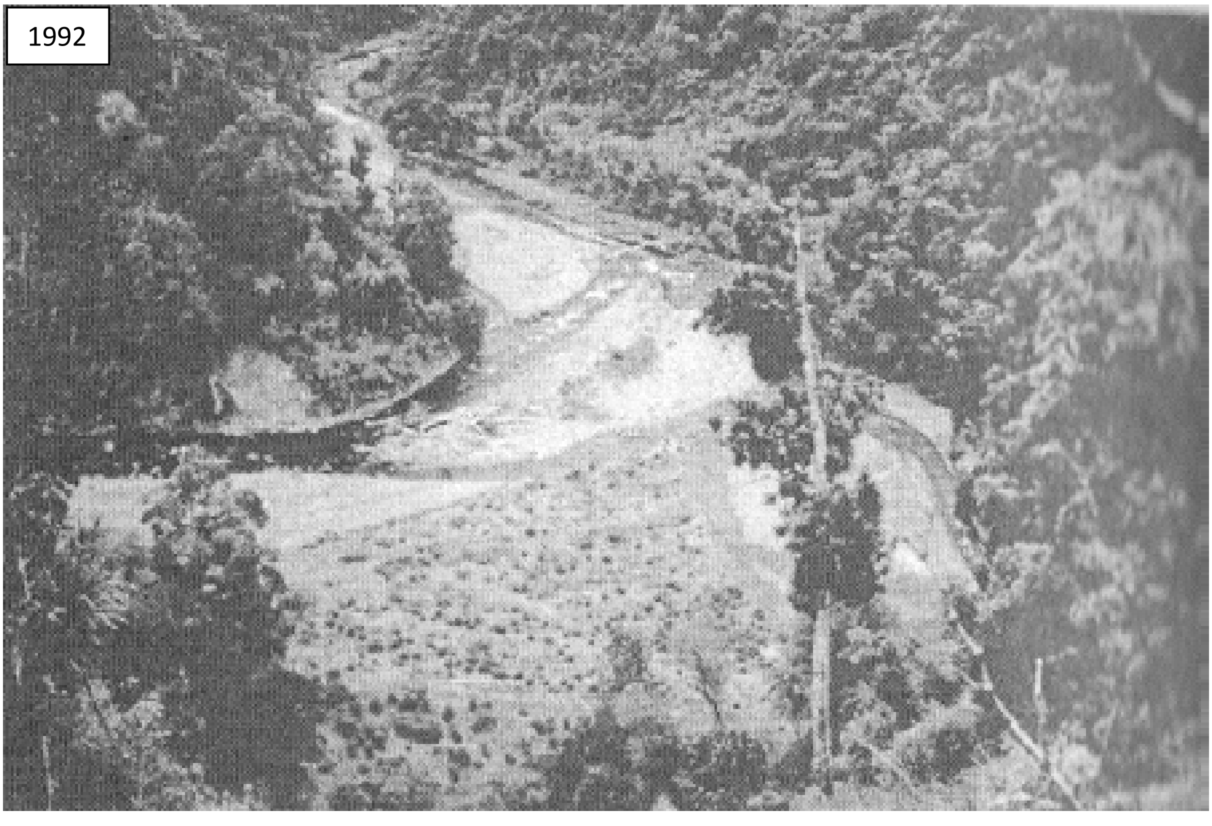


Figure 4-2: Waipa/Tunawaea confluence 44 days after the Tunawaea Landslide dam collapse. Note the view is looking downstream from the left bank of the Waipa with flow in the Waipa entering from the left of the photograph and flow from the Tunawaea entering from the right of the photograph. From Riley et al. (1993).

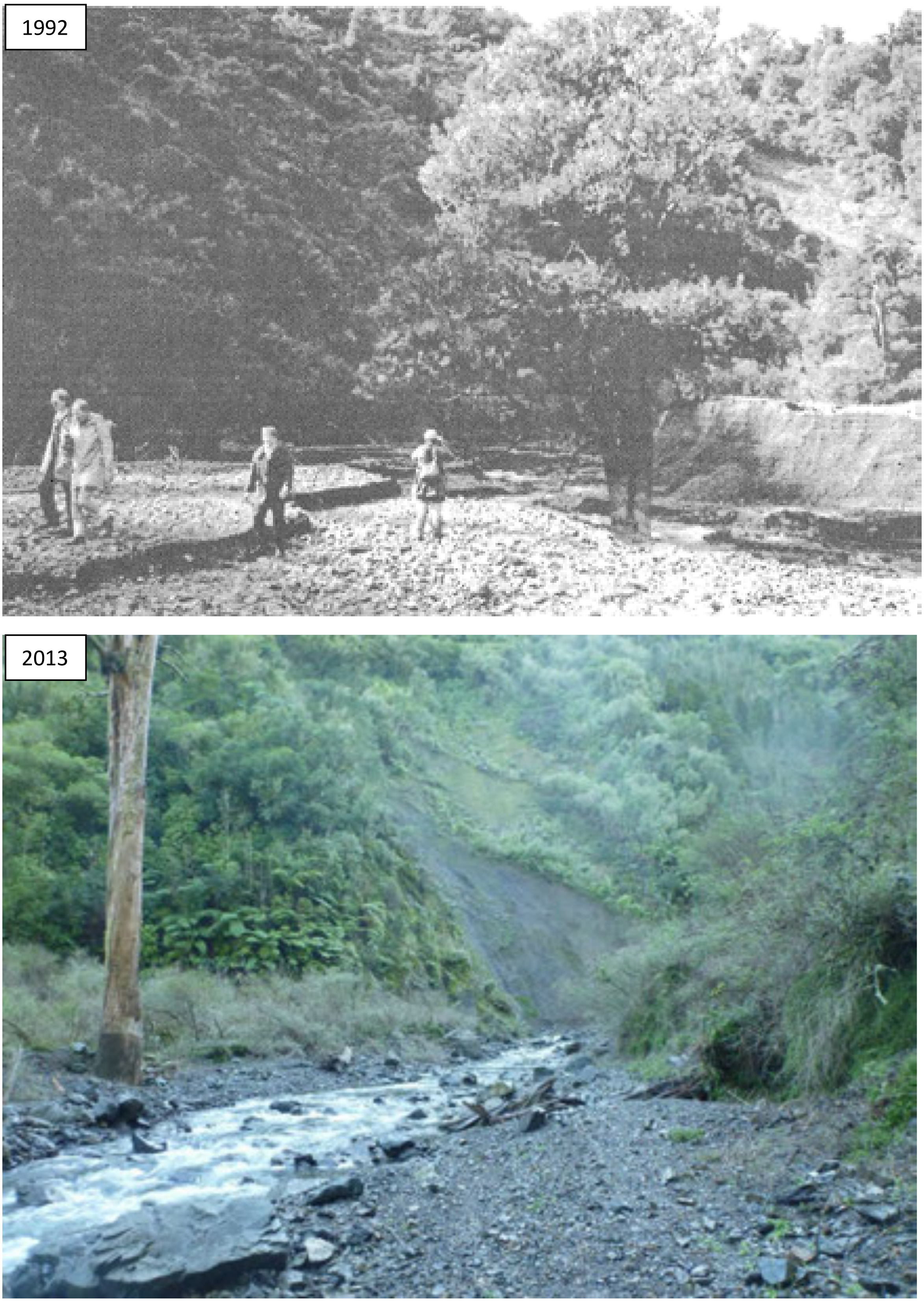
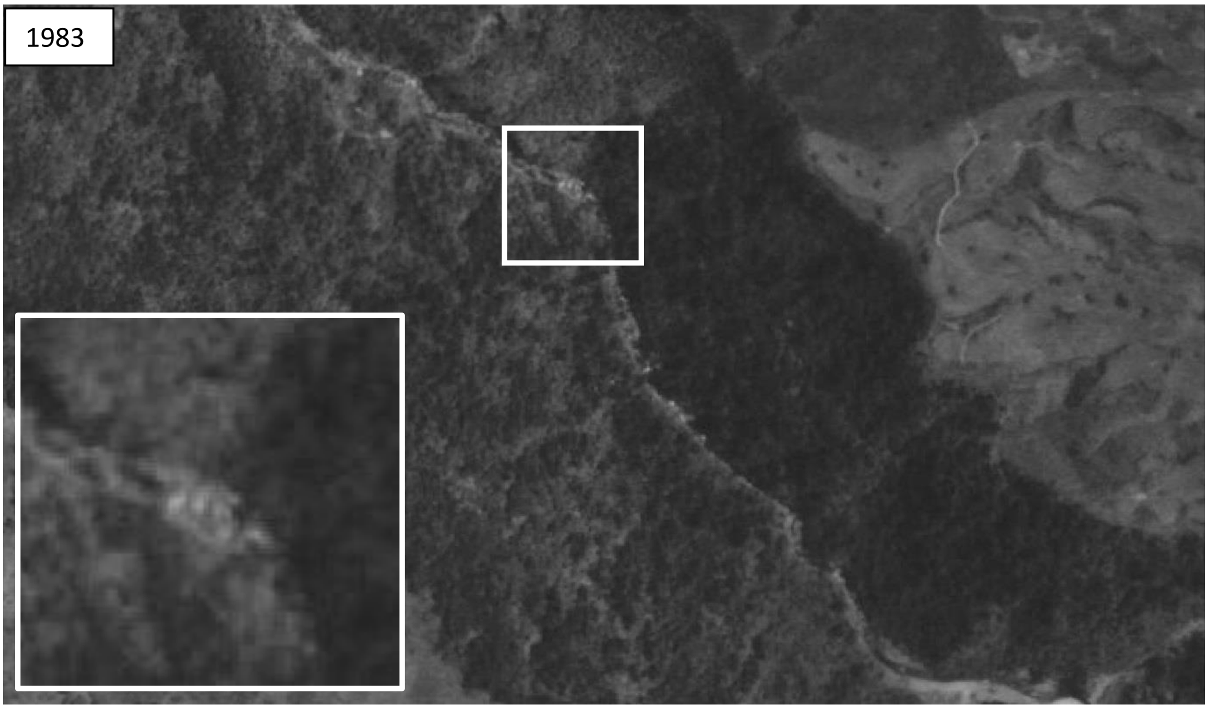
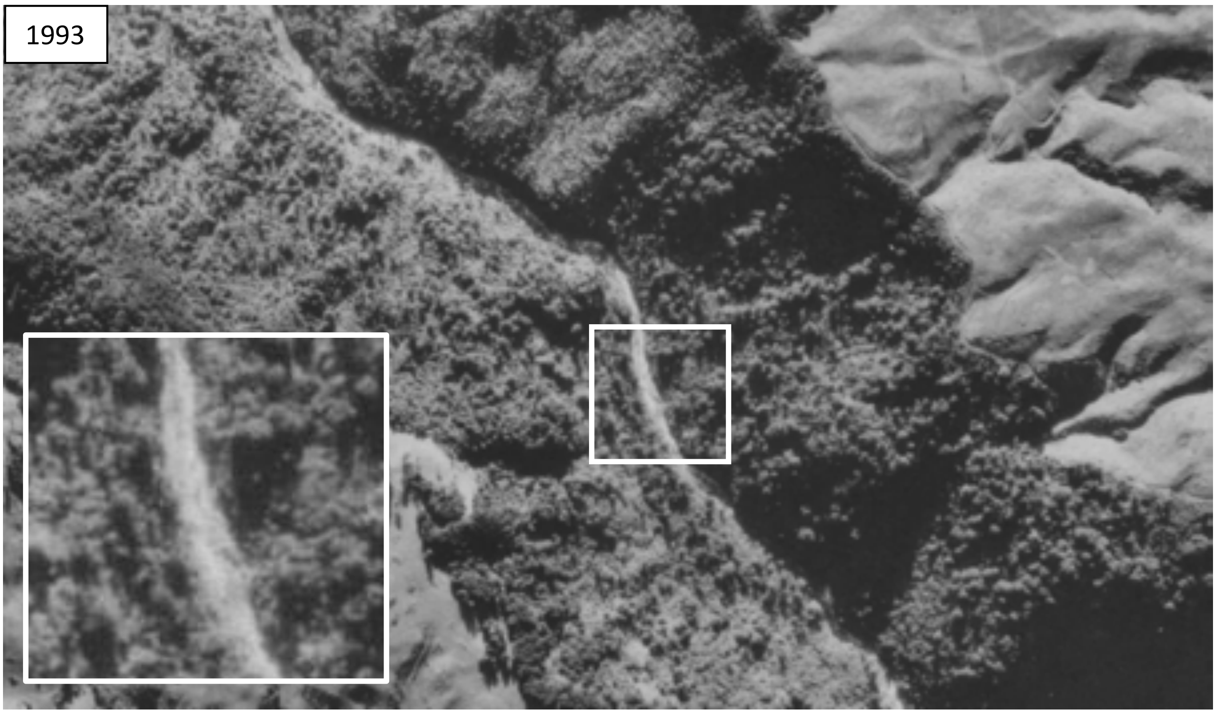


Figure 4-3: Large kahikatea tree in the Tunawaea Stream, approximately 100 m upstream of the Waipa confluence, in 1992 and in 2013. The 1992 photograph is from Riley et al. (1993). Both photos are taken looking upstream.

4.1.2 Ignimbrite gorge reach

The ignimbrite gorge reach is approximately 1.5km long and starts immediately downstream of the Tunawaea confluence. This reach is steep (2-3%) and narrow (15-25 m wide) and comprises a series of cascades (short drops and pools) where the water spills around large (~1.5 m diameter) ignimbrite boulders. Figure 4-4 presents the aerial photographs of this area. The resolution of the 1983 aerial photograph is fairly poor, however, patches of white-water (from the cascades) are visible. These patches of white-water are no longer apparent on the 1993 aerial photograph, and the reach instead gives the impression of being buried in gravel. By 2002 the boulders and cascades become visible in the reach again, indicating that this reach cleared of gravel in the decade following the landslide dam failure. Narrow lateral bars of gravel are still apparent in the reach indicating that gravel is still passing through this reach. The 2007 and 2012 aerials appear much the same as the 2002 aerial, with perhaps more boulder exposure in 2012.




1993


2002

Figure 4-4: Aerial photographs showing changes in the ignimbrite gorge reach. Box inserts provide a zoom in at selected sections of the reach to highlight cascades, gravel burial or bars. Note flow is from bottom right to top left.

4.1.3 Downstream of gorge reach

Downstream of the ignimbrite gorge reach the Waipa River remains highly confined but the gradient reduces (0.7-1.1%) and the river widens, with the active channel up to 100 m wide in places. At the downstream end of this reach there is a short (160m long) bedrock pinch in the valley, forming a local constriction. Figure 4-5 presents the aerial photographs of part of this reach including the pinch. In 1983, prior to the Tunawaea Landslide, this reach comprises a single thread low flow channel with occasional point bars where the valley widens. The 1993 photograph indicates that this reach has approximately doubled in width. This is unsurprising as the peak flood wave generated when the Tunawaea dam breached would have been well in excess of a 100 year event in this reach (see Section 1.2; Parkin et al., 1993). It's highly likely that the dam breach flood wave would have removed riparian vegetation and scoured any easily erodible bank material. The 1993 photograph also shows that this reach is filled with gravel, including through the pinch, and the low flow channel is braiding across its surface. Braiding activity is also clear on the 2002 photograph, and while some of the gravel has started to clear from the pinch the low flow is braiding immediately upstream of the pinch and there are large gravel deposits immediately downstream where the channel widens. In 2007 the low flow channel is reverting to a single thread, forming long alternate bars. Some of these appear to have been planted with rows of trees, but many of the gravel bar surfaces also look like they are naturally revegetating. In 2012 the low flow has completely reverted to a single thread channel but many bars appear clearer of vegetation than in 2007, perhaps as a result of a floods in the intervening period, and there is still clearly more gravel stored in this reach than prior to the landslide.

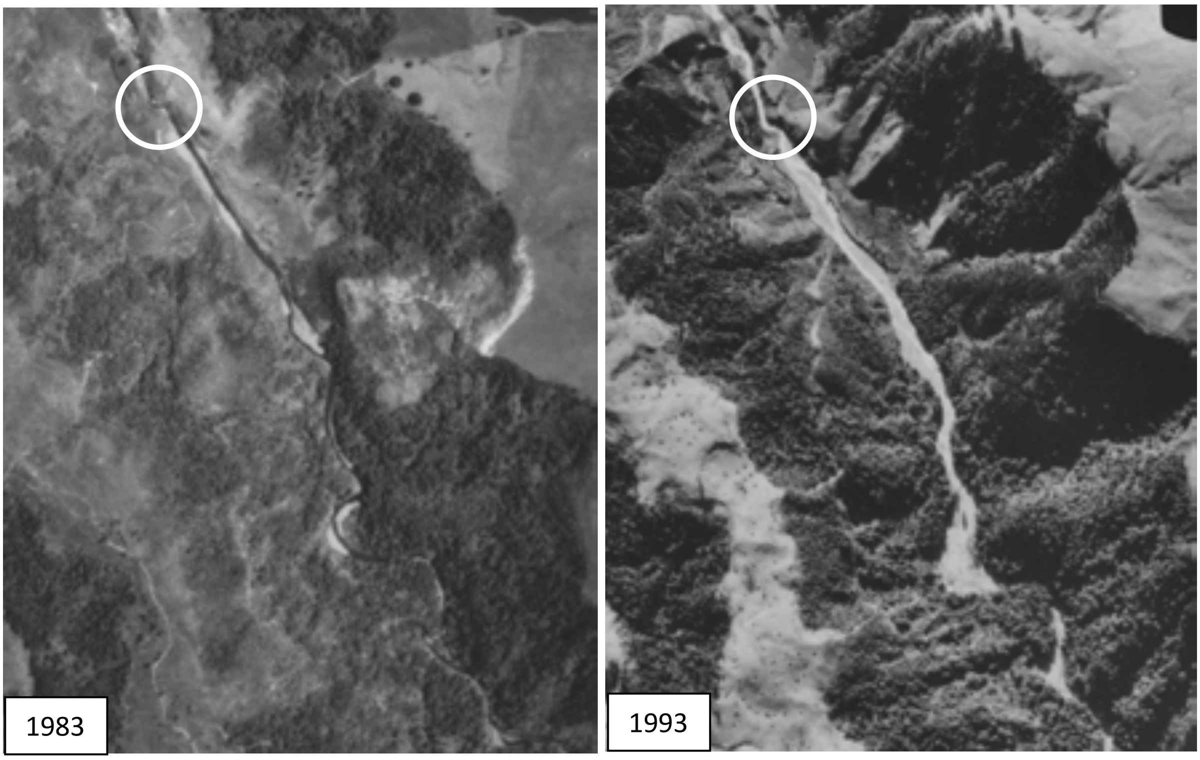
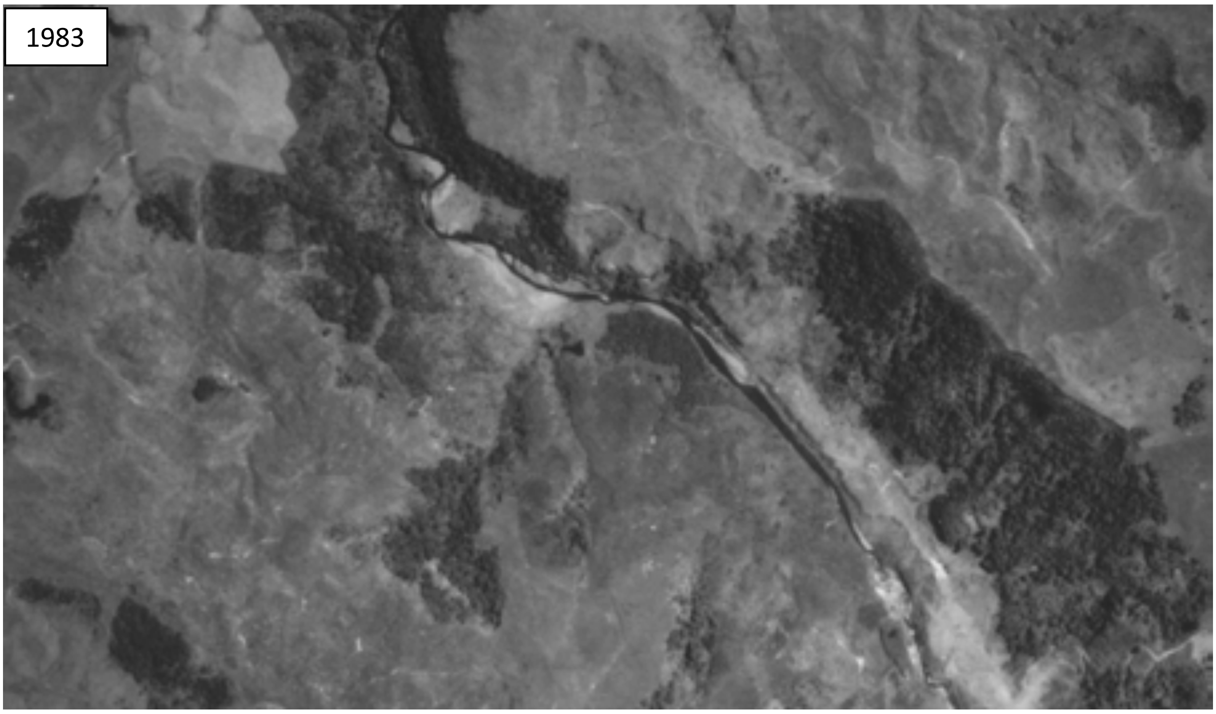


Figure 4-5: Aerial photographs showing changes in the reach downstream of the ignimbrite gorge. Note flow is from bottom to top. The circled area indicates the location of the bedrock pinch.

4.1.4 Pumice terrace reach

The pumice terrace reach has undergone substantial change following the Tunawaea Landslide. The pumice terraces are approximately 16m high and comprise very fine (Figure 3-3) pumice and ash deposited during the Taupo eruption that occurred in 186 AD. Figure 4-6 presents the aerial photographs of this area. In 1983 most of this reach is 40-50 m wide. The channel is straight through the main pumice terrace section and then becomes sinuous downstream. There are occasional lateral or point bars. It is possible that the biggest change in this reach occurred soon after the Tunawaea Landslide, but unfortunately the 1993 aerial photograph is missing for this reach so we are uncertain of the timing of change in this area. The changes are very well captured on the 2002 photograph which shows the active channel has widened to around 125-175 m between valley or terrace margins. A huge volume of pumice terrace material has eroded away and the low flow channel is braiding across extensive gravel deposits. One low flow channel runs hard against the right bank and another has broken left leaving a large vegetated island. In 2007 extensive planting is apparent (rows of trees), keeping the low flow channel pushed to the left bank. However, the low flow channel is still braiding a little around mid-channel and alternate bars. By 2012 the planted trees have become more established and the low flow channel has further reverted to a single thread and looks to have incised. There are still active lateral and mid channel bars of gravel throughout this reach.



2002

2007

Figure 4-6: Aerial photographs showing changes in the pumice terrace reach. Note the 1993 aerial photographs unfortunately miss this section of the Waipa River. Flow is from bottom to top.

4.1.5 Partly confined reach

Downstream of the pumice terraces the Waipa River enters a partly confined reach. While not as narrow as the gorge, the valley margins are relatively narrow, more so than through the pumice terrace reach, and the valley gradually widens through this reach from approximately 50 m to 200 m wide. This partly-confined setting limits the ability of the river to adjust laterally, but there are small pockets of floodplain within the valley margins. Figure 4-7 presents the aerial photographs of one of the wider sections of this reach where there has been some loss of floodplain over the period since the Tunawaea Landslide. The 1983 aerial photograph shows the low flow channel meandering within the valley margins, alternating from one valley wall to the next. There are several large point bars present and in one location the low flow channel splits around an island. In 1993, the low flow channel has widened and there are areas of floodplain erosion apparent, for example in the circled area. In 2002 changes are apparent further upstream, for example in the boxed area where there appears to have been loss of vegetation and sediment deposition across the floodplain on both sides of the river. The 2007 and 2012 photographs show revegetation, including some planting within the area marked with a triangle. Between 2007 and 2012 there is also some bank erosion on the right bank within the area marked with the triangle. In 2012 there was still active movement of gravel through this reach, however the size of gravel bars reduces downstream. Based on the aerial photograph evidence it appears that the bottom end of this reach, at a river distance of 16 km (as defined in Figure 2-2), is the approximate extent to which the Tunawaea gravel slug has progressed.

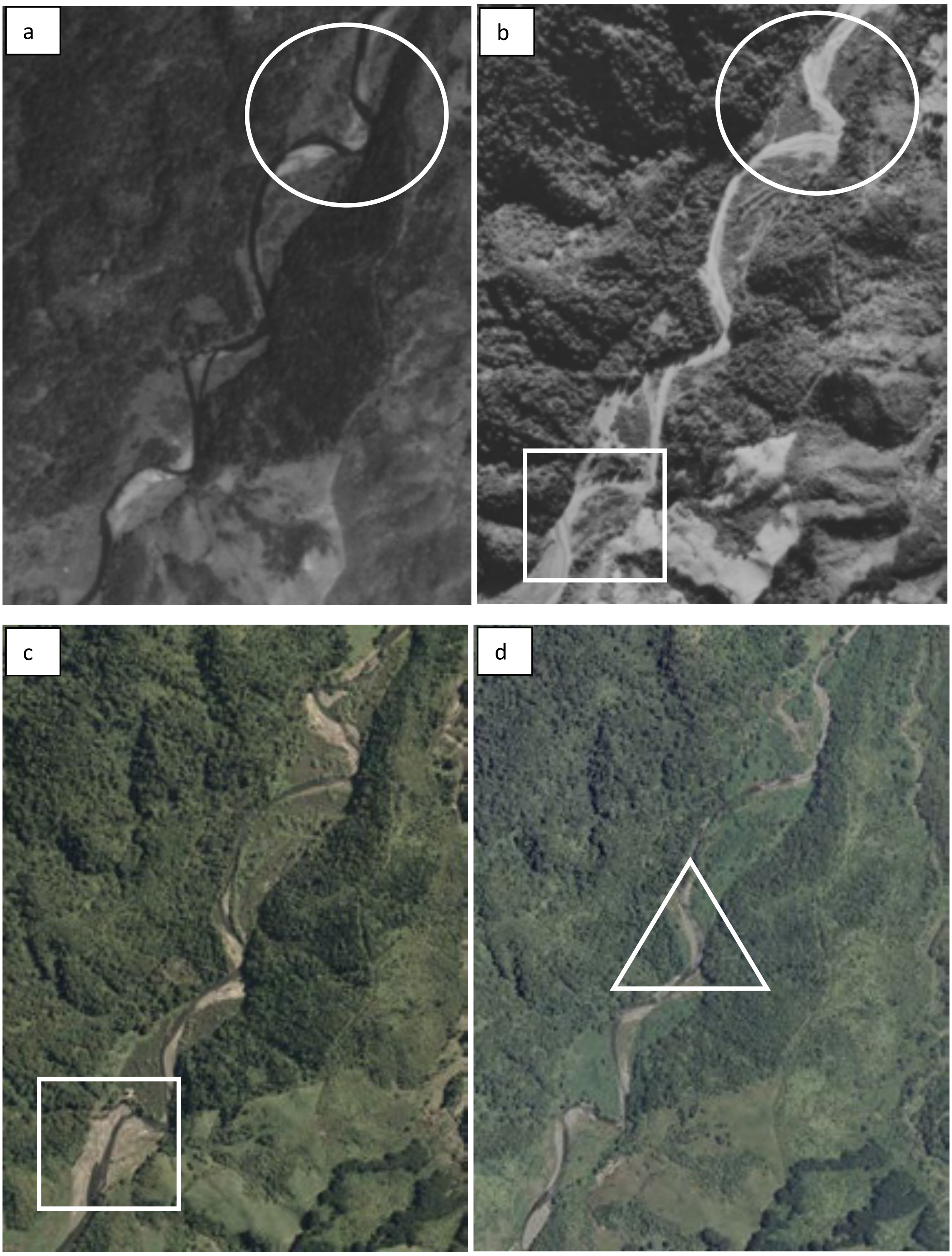
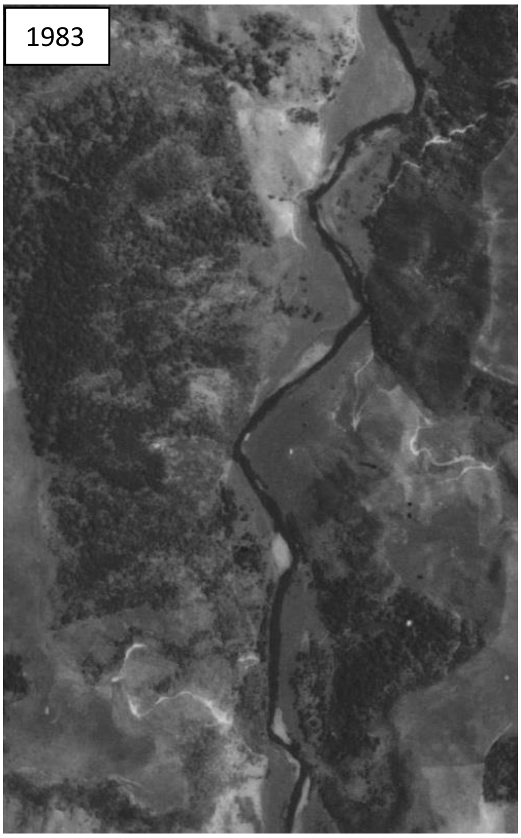

a
b
c
d

Figure 4-7: Aerial photographs showing changes in the semi-confined reach. Note flow is from bottom to top. Areas noted with a circle, box or triangle indicate locations of notable change.

4.1.6 Floodplain pocket reach

Further downstream the valley continues to open out. The river is still partly confined by the valley margins but the valley ranges from approximately 150 m to 350 m wide, allowing the formation of larger floodplain pockets. Geomorphically, this reach is fairly similar to the adjacent (partly confined) reach upstream, however, bars within this reach are few and far between, and this appears to have been the case since before the Tunawaea Landslide. Figure 4-8 presents the aerial photographs of the lower part of this reach, just upstream of Toa Bridge. These photographs all show a narrow low flow channel with an occasional small gravel bar. There are a few areas of bank erosion noted, for example in the area circled where the channel cuts into the left bank by approximately 40 m.


1983


1993


2002


2007

Figure 4-8: Aerial photographs showing changes in the floodplain pocket reach. Note flow is from bottom to top. The circled area indicates a location of bank erosion.

4.1.7 Upper unconfined reach

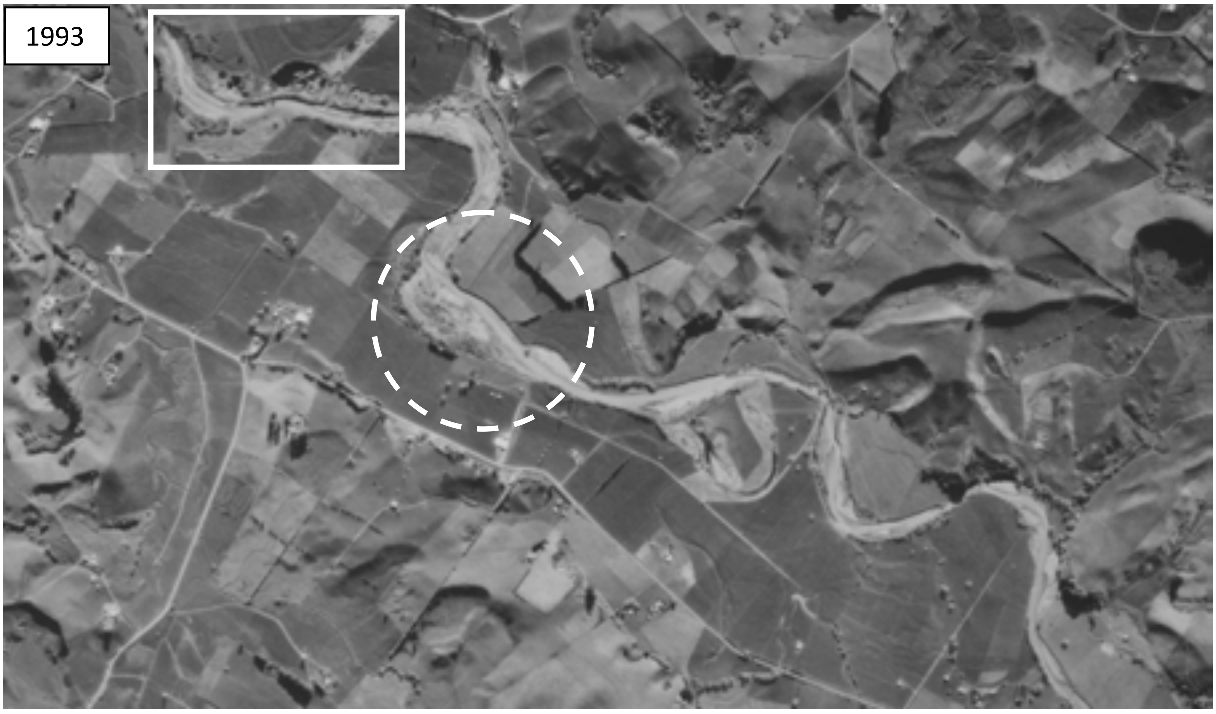
Downstream of Toa Bridge the Waipa River is mostly laterally unconfined by its valley margins. It does pass through one area where the valley closes in to 150 m wide, and this section of the reach is presented at the upstream end (bottom) of each of the aerial photographs in Figure 4-9. This reach, like the floodplain pocket reach upstream, appears very stable in the photographs over the period from 1983 to present. Gravel bars are very small and infrequent along this reach, and the channel alignment has been consistent and controlled by riparian vegetation (willows).


1983
1993
2002
2007

Figure 4-9: Aerial photographs showing changes in the upper floodplain reach. Note flow is from bottom to top.

4.1.8 Cut-off and extraction reach

Between river distances 29-40 km is a laterally unconfined reach, of moderate sinuosity, that we refer to as the cut-off and extraction reach. This is because the aerial photographs reveal a number of past meander cut-offs (of which the exact timing is unknown, but we assume these are engineered cut-offs made following the 1958 flood) and also locations of gravel extraction on bars and in the adjacent floodplain. This reach has undergone substantial change in the period following the Tunawaea Landslide. As gravel from the Tunawaea Landslide does not appear to have arrived at the reaches upstream, we infer that changes in this part of the study reach are the result of the river adjusting to a shortened river length which subsequently increases the gradient. Figure 4-10 presents the aerial photographs of part of this reach. The 1983 aerial photograph clearly shows an old meander cut-off (circled area). This location is just downstream of Rendall’s Bridge (Figure 2-1). An area of gravel extraction just adjacent to the channel is outlined with a box. The 1993 aerial photograph shows that the channel has widened throughout, including substantial erosion of the right bank both upstream and downstream of the cut-off. The area of greatest erosion is circled with a dashed line. There has also been additional extraction on the right bank floodplain, digging a pond in an area previously covered with trees. The boxed area has been extended to show the moving extraction region. By 2002 the extraction has ceased but the pond remains surrounded in a circle of trees. This photograph shows large areas of revegetation and planting, but bank erosion is continuing. For example, in the dashed circle area the left bank has revegetated but the bank erosion on the right has increased. There has also been erosion of the right bank downstream of the site of previous extraction. In 2007 most areas that were bare gravel in 2002 have revegetated, or been planted, and there is very little bare gravel remaining. In 2012 there is some renewed erosion on the left bank upstream of Rendall’s Bridge, and river engineering works were carried out at this location between our two surveying field visits in 2013. There has also been some spur planting in the area indicated with a triangle to push the river back to the right and reclaim some of the previously eroded left bank.



2002

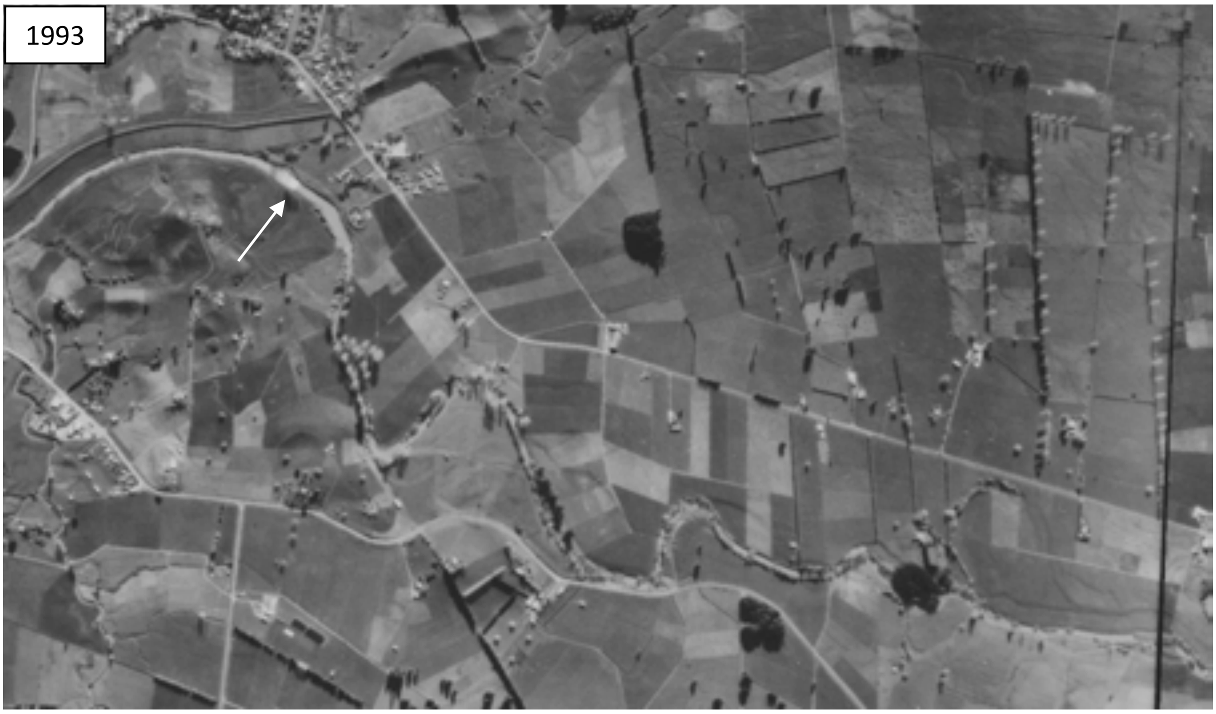
2007

Figure 4-10: Aerial photographs showing changes in the cut offs and gravel extraction reach. Note flow is from bottom right to top left. Areas noted with a circle, box or triangle indicate locations of notable change.

4.1.9 Downstream reach

The Waipa River continues to be laterally unconfined, bordered by extensive floodplain, all the way down to Otorohanga Bridge (and beyond). This reach includes the weir adjacent to the Otorohanga water treatment plant. As evident on the aerial photographs (Figure 4-11), this reach has remained laterally stable through the study period. The only clear changes on these photographs are a small amount of erosion in the vicinity of the weir between 1983 and 1993 and perhaps tree removal and replanting in the sweeping curve between the weir and the Otorohanga Bridge. Overall, this reach has been remarkably stable.


1983


1993


2002


2007

Figure 4-11: Aerial photographs showing changes in the bottom reach. Note flow is from right to left. The weir is marked with a white arrow on each photograph.

4.2 Analysis of historic surveys

4.2.1 Tunawaea

Following the 1991 landslide and subsequent dam break a number of long section profiles were surveyed of Tunawaea Stream downstream of the landslide (Riley et al. 1993). The water surface profile and the elevation of distinct river terraces were resurveyed in July 2014 and are overlaid on the original survey data in Figure 4-12. Since the final historic survey, which was done 44 days after the landslide dam failed, the channel bed has lowered approximately 8 m over much of the lower Tunawaea but is still approximately 5 m higher on average than the original pre-landslide bed elevation. River terraces surveyed in July 2014 are representative of bed levels at different stages of post dam-break river bed incision.

In order to calculate approximate volumes of sediment stored and then released in the lower Tunawaea the likely maximum aerial extent of gravel build up was identified and digitised from the aerial photography (Figure 4-13). Based on the digitised area and an assumed average incision depth of 7 m from peak gravel build-up[1] the volume of gravel temporarily stored and subsequently released was estimated at 250,000 m^3. This estimate was used as a lower bound of the landslide derived gravel volume entering the Waipa.

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[1] The average re-working thickness from peak gravel build up (day 2) to surveyed 2014 water level in Figure 4-12 is approximately 15 m. However, raised terraces remain to either side of the channel and the original valley sides have been re-exposed at the edges of the gravel flats so the average thickness of the re-working is likely much less than 15 m.

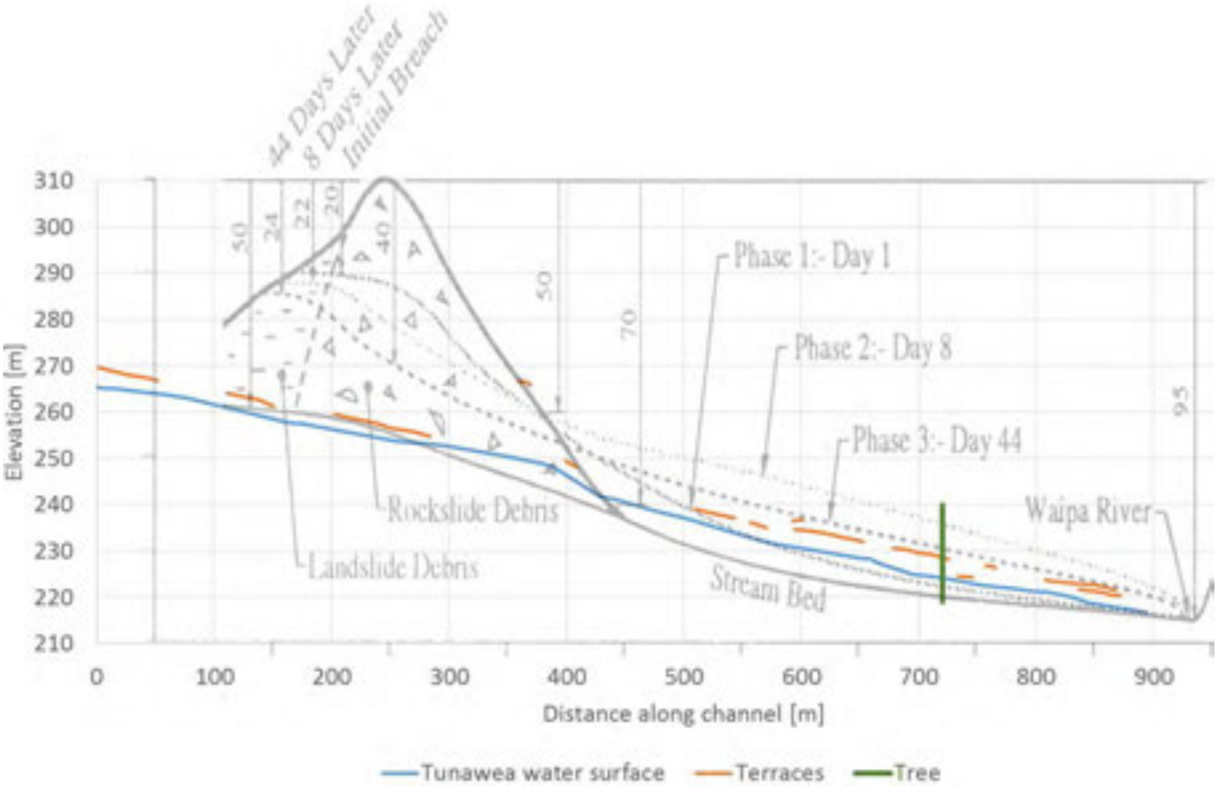

Figure 4-12: Long-profile of the Tunawaea (Riley et al. 1993), overlaid with water and terrace surface profiles surveyed by NIWA. The location and approximate size of the Kahikatea Tree described in Section 4.1.1 and shown in Figure 4-3 is also marked.

Figure 4-13: Approximate maximum extent of gravel build up in the lower Tunawaea. Maximum gravel extent shown hatched in red overlaid on 2002 aerial photography. Landslide site visible further upstream (right) and Waipa visible downstream (left, flowing from bottom to top).

4.2.2 Waipa

Mean active channel bed level of the historic cross-sections relative to the current cross-sections is shown in Figure 4-14. The comparison of mean bed levels shows different patterns in different reaches:

- **<7 km - Upstream of Pumice Terraces:** No historic data available.
- **7-21 km - Pumice Terraces to Toa Bridge**: Up to 0.3 m aggradation since 2008. No pre-2008 data available.
- **21-25 km:** Some historic aggradation up to 0.5 m from 1989 to 2008.
- **25-30 km:** Degradation between every survey since earliest survey in 1978/79. Degradation of mean active bed levels in excess of 1 m. Rate of degradation may be reducing over time.
- **30-37 km:** Aggradation between every survey since 1989/90, with maximum rise of mean bed levels in that period greater than 1 m. In the period 1958 to 1978 massive degradation occurred (up to 3 m).
- **37-43 km - Upstream of Otorohanga Weir:** Relatively stable bed levels since 1978/79 survey. Significant degradation prior to this (1-1.5 m between 1958 and 1978/79).

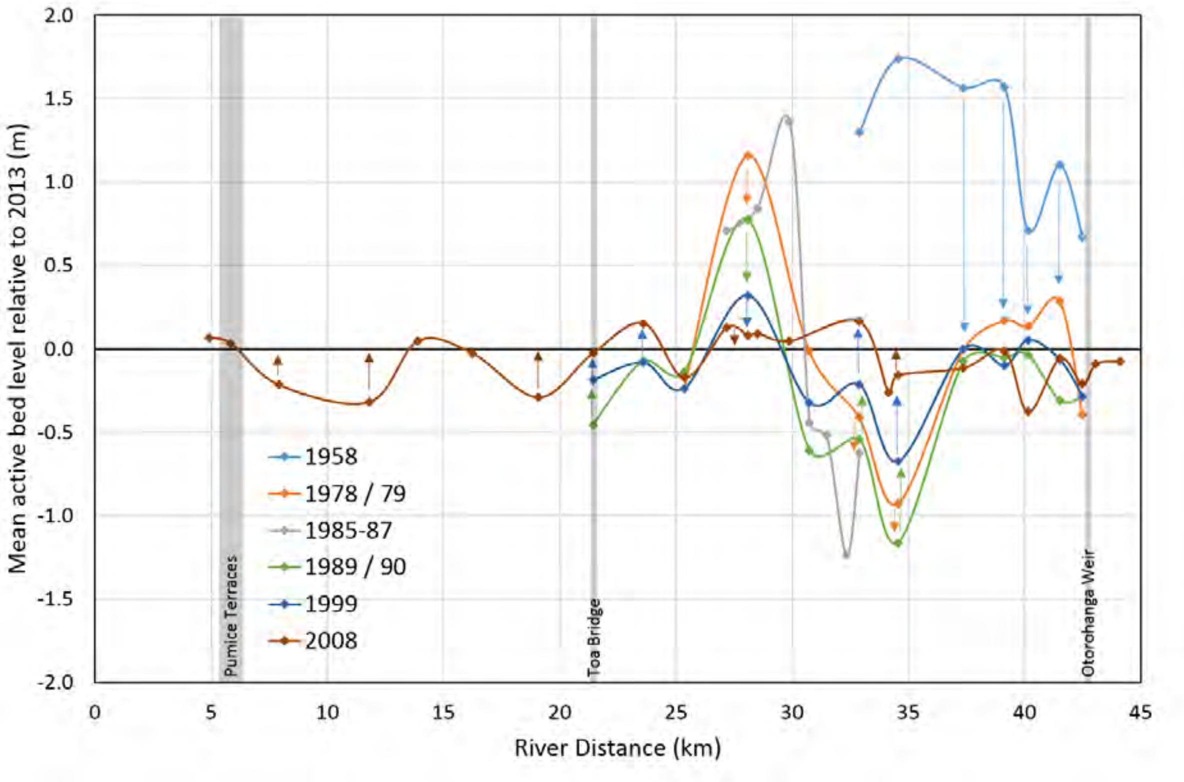

Figure 4-14: Difference in mean active bed level between historic and most recent surveys.

4.3 Model calibration results

4.3.1 Hydraulic calibration

During hydraulic calibration, form roughness (expressed in terms of Manning's 'n' coefficient) was adjusted from 0.006 to 0.015, equivalent to a total roughness in the channel of approximately 0.029. A comparison of modelled and surveyed flood peak levels in the calibrated model is shown in Figure 4-15. The root-mean-squared error in water surface elevation in the calibrated model was 0.17 m. For the purposes of morphological modelling this level of accuracy is appropriate. Remaining differences between modelled and surveyed water levels are likely due to a combination of:

- Morphological change between the cross-section survey in June-October 2013 and the calibration event in July. Significant change was observed in this reach, particularly in the bend immediately upstream of Rendall's Bridge (section 4.1.8).
- Differences between quasi-steady flow assumptions in the model and time-varying flood peak.
- Difficulties in accurately identifying flood level from wrack marks. Flood levels may have been influenced by local variations in water level and may not be representative of the cross-section average water level.

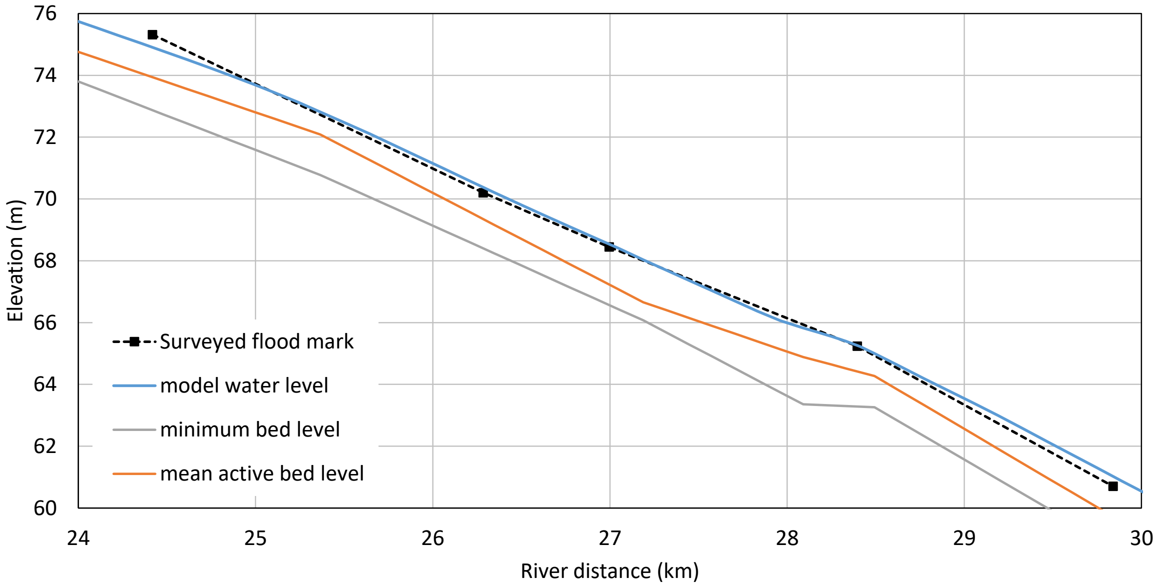

Figure 4-15: Comparison of modelled and surveyed flood peak level 12 June 2014.

Unfortunately, due to access, timing and difficulties in accurately identifying and pegging peak level flood levels, data were only collected for the reach from 24.4 to 29.8 km. However, as this reach is hydraulically similar to much of the lower part of the model the calibrated form roughness was applied to the whole reach from 5.8 km to the downstream of the model (44.1 km). Upstream of 5.8 km form roughness is higher due to the presence of bedrock outcrops and ignimbrite boulders. It was not possible to hydraulically calibrate form roughness estimates for this reach as no data were available.

4.3.2 Morphological calibration

During morphological calibration, adjustments were made to the model to improve calibration of bed level change and sediment composition. These adjustments included:

- **Form roughness:** In the upstream part of the model form roughness was adjusted. Initially form roughness was too high, resulting in grain stresses and bedload transport capacities that were too low and creating excessive sediment deposition within the gorge reach.
- **Additional assumed cross-sections:** Additional assumed cross-sections were inserted to stabilise the model and better represent areas of rapid cross-section shape/slope change. Additional sections were inserted to better represent the short constricted pinch reach at 5 km and around the Otorohanga Weir.
- **Bedrock elevation:** Bedrock elevation was adjusted to allow smoother transition between reaches with and without a specified bedrock layer (e.g. at the downstream end of the main gorge reach). Bedrock was also inserted at the pinch reach at 5 km to better represent this short bedrock reach.
- **Bed sediment composition:** Some minor adjustments to the starting surface and sub-surface bed sediment composition were made by changing the reaches over which sampled data were averaged and applied to the model.
- **Upstream sediment feed rate:** The feed rate from the upper Waipa was increased by 50% from initial estimates to prevent excessive erosion prior to the landslide.
- **Tunawaea sediment feed:** The rate coefficient and decay rate for bedload supply from the Tunawaea Landslide into the Waipa (see Section 3.7.4 for a definition of these terms) were adjusted within the uncertainty bounds of estimates of sediment storage volume changes experienced in the Lower Tunawaea (see Section 4.2.1 for details of analysis of landslide sediment volumes). The half-life was increased to 900, days and the initial rate coefficient adjusted to increase the total landslide-derived bedload feed to 420,000 m^3. It should be noted that even with a long half-life very high rates of bedload delivery are calculated in the first hours following the landslide dam failure due to the high flows in Tunawaea Stream released as a result of the breach. A timeseries plot showing the final supply rate is shown in Figure 4-16.
- **Distribution of deposited sediment between bed layers:** In GRATE the Toro-Escobar et al (1996) transfer function is used to control the distribution of deposited sediment between the active and top subsurface sediment layers (Walsh 2010). The χ parameter of the transfer function was reduced from 0.7 (default) to 0.15 to prevent the build-up of overly fine subsurface layers during post landslide deposition and better match observed sediment composition. As the default value of the χ parameter was derived from laboratory experiments and there is little other guidance available it was felt that this large change was appropriate.

The final calibrated values of cross-section specific parameters (e.g. bedrock elevation and form roughness) are shown in Appendix B and global parameters are listed in Appendix C.

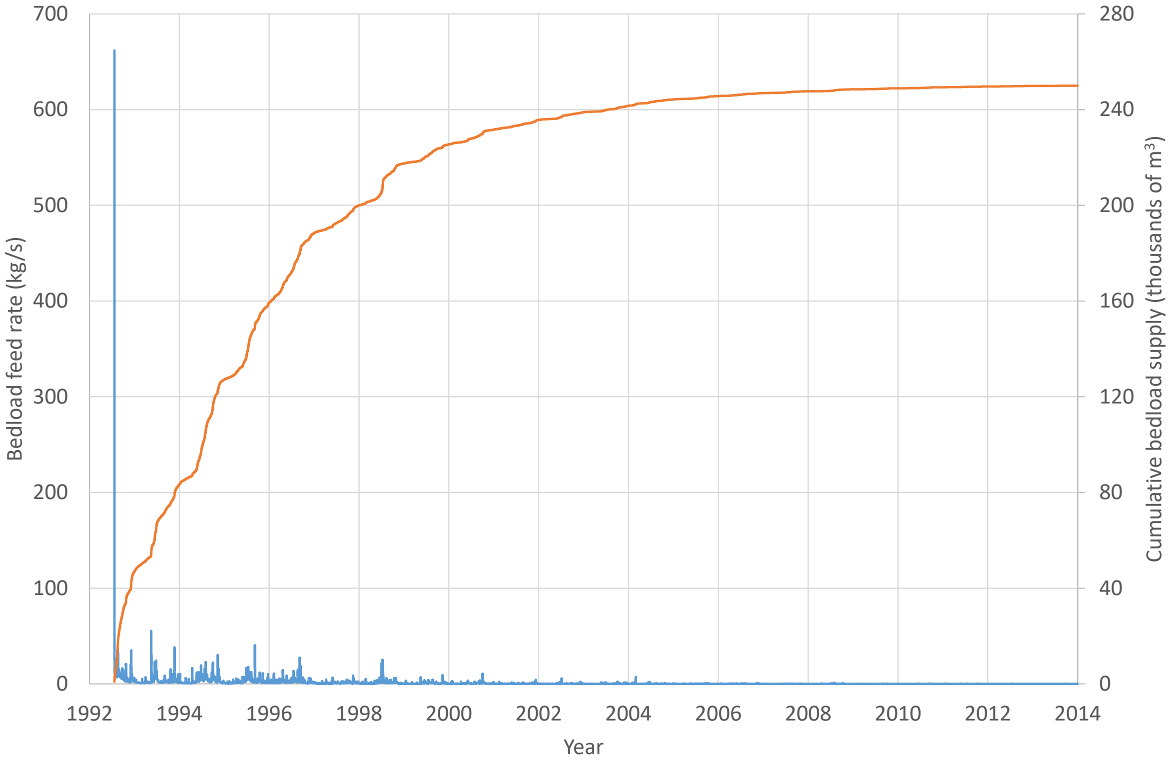

Figure 4-16: Model bedload feed representing Tunawaea Landslide inputs to Waipa. Feed rate in blue, cumulative volume delivered in orange.

Comparisons of the modelled and sampled/surveyed sediment composition and bed level change (extracted from the model at July 2014) are shown in Figure 4-17 and Figure 4-18 respectively. In general the surface and subsurface sediment compositions in the calibrated model compares well with the sampled data. In most reaches model sediment compositions are within the range of variability exhibited by the nearby samples. One notable anomaly in the model sediment composition is in the gorge reach below the Tunawaea confluence (1 to 2.5 km) where the model appears to have very fine sediment in Figure 4-17. However, the sediment composition shown in this reach is largely irrelevant as erosion in this reach is limited by a specified bedrock layer in the model. The model has eroded down to the bedrock layer in this reach and has no subsurface sediment and only a very thin and highly mobile active layer. Upstream and downstream of this gorge reach (0 to 1 km and 2.5 to 7 km) the model surface composition deviates markedly from the observed sample compositions. However, the surface samples in these reaches were finer than the subsurface which is unlikely to be realistic. Due to the constricted nature of the channel in these reaches it was difficult to find accessible and representative sampling sites and there is high uncertainty in the sampled compositions so the model results seem reasonable.

The bed level change in the model matches the patterns of surveyed change well in the lower 20 km of the model where historic data are available. The model shows slightly too much erosion in the upstream part of the reach (20 to 32 km) and slightly too much deposition in the downstream part of the reach (37 to 43 km).

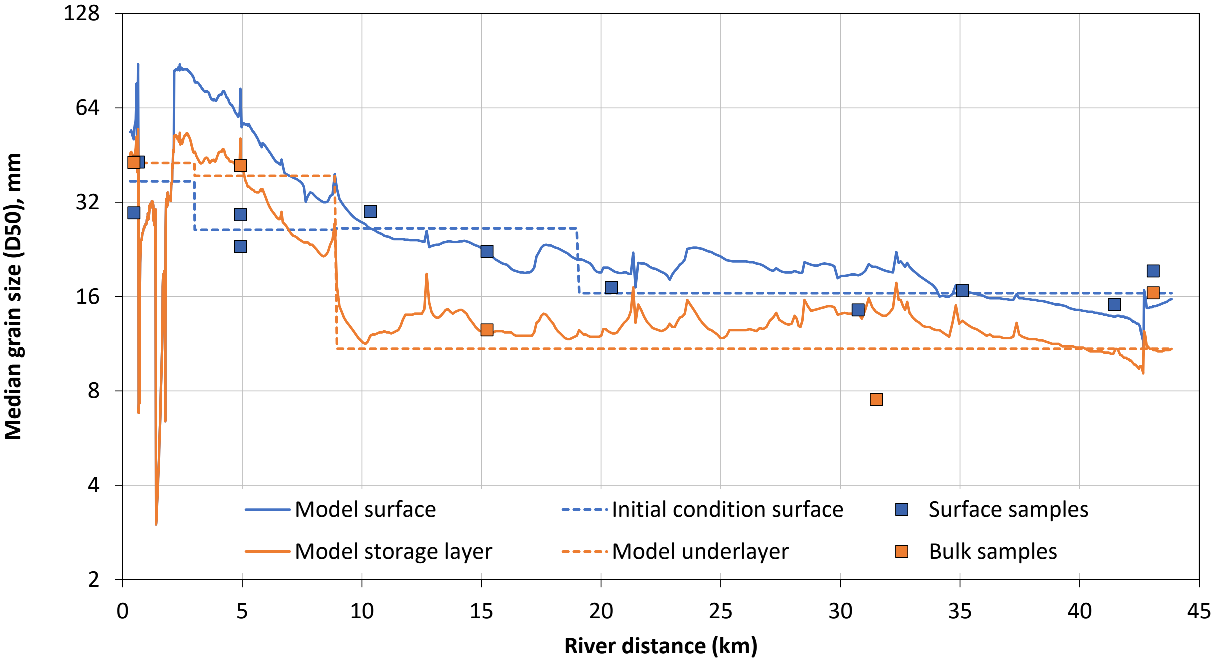

Figure 4-17: Comparison of model and sampled surface and sub-surface sediment composition. Model results from July 2014, coinciding with most of the sediment data collection (some surface sediment data were collected in July 2013 but model results are very consistent between 2013 and 2014.

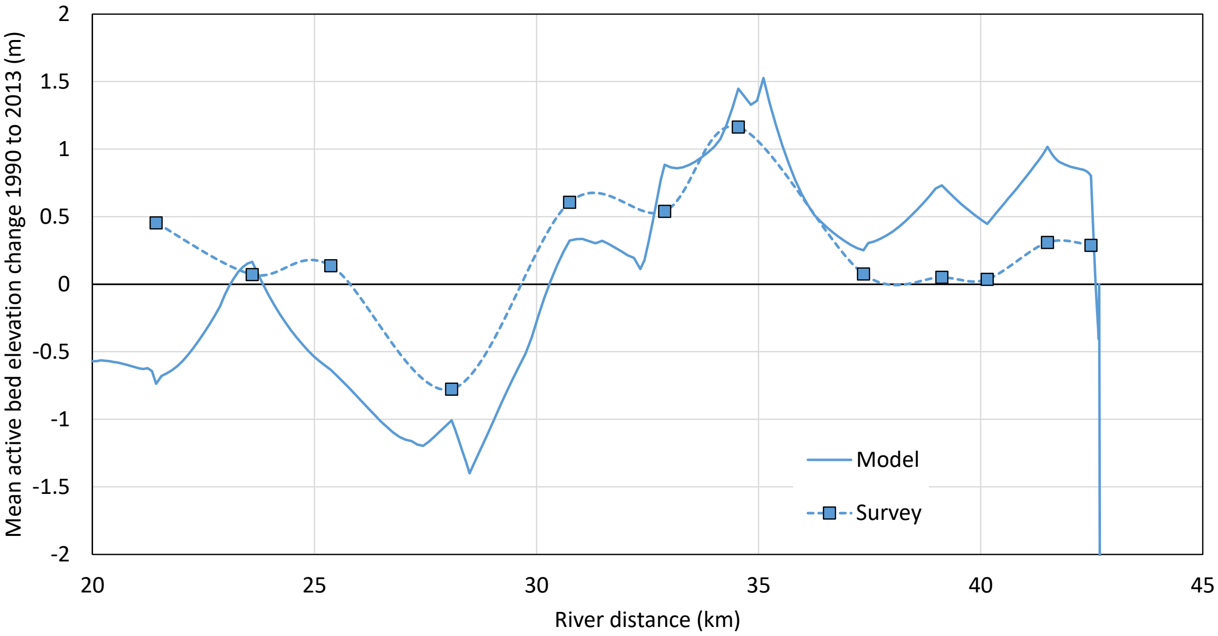

Figure 4-18: Comparison of modelled and surveyed mean active bed level change from 1990 to 2013. Comparison is only shown for the reach from 20 km downstream as no 1990 survey data are available upstream of this point.

Upstream of this reach no historic survey data are available except for 2008, and the observed morphological changes from 2008 to 2013 are quite small and longitudinally variable (see Figure 4-14). The bed level comparison in this reach is also influenced by significant cross-section shape change in some locations. These factors make it very hard to draw useful conclusions about the calibration from these data.

In order to calibrate the upstream part of the model the bed level change results were compared reach by reach against anecdotal observations of morphological change and observations from the aerial photography analysis. It must be remembered that as a 1D model GRATE can only capture vertical change in cross-sections, requiring some additional interpretation when channel response has included width changes.

- **Tunawaea confluence reach (0.6 km):** Although bed levels in the Tunawaea rose dramatically (up to 20 m) following the landslide failure there appeared to be only a small effect on Waipa bed levels (<2 m) at the confluence (see surveyed Tunawaea long section profiles following the landslide dam failure reproduced in Figure 4-12). The calibrated model results show a maximum increase in bed levels of approximately 1 m, returning to pre failure levels by approximately 1996 and staying relatively constant after that. This seems reasonable.
- **Ignimbrite gorge reach (1 to 2.5 km):** The aerial photograph analysis suggested there was some gravel build-up in the gorge visible in 1993 that had largely gone by 2002. The model is consistent with this, showing increasing build-up of gravel in the upper and lower parts of the gorge after the Tunawaea Landslide dam failure in 1992, peaking in 1995, and then reducing back to pre-landslide levels by 1998 except for the downstream-most part of the gorge which was affected by sediment backing up from downstream.
- **Downstream of gorge (2.5 to 5.2 km):** The aerial photograph analysis shows significant build up in gravel through this reach in 1993, including through the pinch at the downstream end of this reach which was a steep narrow boulder strewn channel in earlier photos. The next photograph in 2002 shows gravel stocks starting to reduce in this reach but still active braiding in several locations. By 2007 the channel is returning to single thread, suggesting degradation, and by 2012 it has fully returned to single thread and the pinch is largely clear of gravel, although there is still more gravel stored upstream of the pinch than before 1993. In the model, gravel build-up occurs rapidly in the upper part of this reach following the landslide dam failure, and by 1993 accumulations of up to 3 m exist, appearing to match the aerial photographs, but the thickness of gravel deposits reduces along the reach and the pinch is only partially buried at its downstream end. By 2002 in the model, the pinch is completely buried and the bed is starting to degrade in the upstream part of the reach. In 2007 and 2012 the model bed is slowly degrading, which is consistent with the aerial photography, but unlike in reality the gravel is never fully cleared from the pinch in the model.
- **Pumice terrace reach (5.2 to 7.2 km):** The aerial photography shows massive bank erosion in this reach resulting from local build-up of gravel following the Tunawaea Landslide. Unfortunately the photographs do not record the timing of this gravel build-up/bank erosion except that it was prior to 2002. Between 2002 and 2007 extensive river engineering work in this reach re-established the channel position, preventing further bank erosion, but the channel is still actively braiding, suggesting it is not yet experiencing significant degradation. By 2012, however, the channel has reverted to single thread, suggesting degradation has occurred. The model results match these

observations well, showing a rapid build-up of gravel after the Tunawaea Landslide dam failure, with a maximum deposition rate around 1995. Bed levels peak in the model in 2006-2007 but then following this peak they tend to stabilise rather than degrade.

- **Partly confined reach (7.2 to 16.4 km):** Aerial photograph analysis suggests that the bottom of this reach represents the current limit of the effect of the Tunawaea Landslide. Changes in this reach are not as marked as further upstream but there appears to be some aggradation within the reach by 1993, continuing in 2002. In 2007 and 2012 some revegetation has occurred but there is also some evidence of continuing gravel movement. Beyond river distance 16 km there is little evidence on the photographs of an aggradation pulse. The model shows aggradation at the upstream part of this reach starting in 1993. At the upstream end of the reach, 1 m of aggradation occurs by 2000 after which the rate of aggradation slows down but continues through to the present day. This aggradation seems to match reasonably well with the observed changes at the upstream part of the reach. Further downstream the model only shows aggradation extending to approximately 9 km, however, a comparison of simulations with and without the landslide (the results of which are described further in Section 4.4.1) show that the landslide effect does extent to approximately 16 km, comparable with the aerial photographs. This suggests that the model is representing the effect of the landslide well but may be showing unrealistic slight degradation of this reach without the landslide.

During morphological calibration a bed sediment mass balance check was carried out to ensure that the model was not gaining or losing sediment (except for the lateral sediment feeds and calculated abrasion losses). The cumulative mass balance error was less than 1.5% over the whole duration of the simulation.

Overall, the model calibrates reasonably well, giving confidence in its capability to make useful predictions of future change. Aspects of the model which deviate from observations and should be considered when interpreting results from model runs into the future include:

- Uncertainty in the accuracy of sampled and modelled sediment compositions in the upstream part of the model around the Tunawaea confluence.
- The model does not fully re-work the landslide derived gravel build-up from the constricted pinch reach at 5 km whereas in reality sediment was fully re-worked from this reach. (One possible reason for this difference is that form roughness is constant over time in the model and is quite high for this reach due to the presence of ignimbrite boulders. In reality when the reach gets drowned by gravel deposits the form roughness would reduce meaning a greater proportion of the shear forces are carried by the grains, increasing transport and causing more rapid re-working of the deposits.)
- The model shows landslide effects extending to 9 km by 2012 whereas aerial photographs suggest they may extend as far as 16 km downstream.
- In the lower reaches of the model beyond the effects of the Tunawaea Landslide the model shows slightly too much erosion from 20 to 32 km, and slightly too much deposition further downstream (37 to 43 km) as shown in Figure 4-18.

4.4 Model future run results

4.4.1 Landslide effects

Based on both photographic observations and modelled results, the study reach has been subject to two key morphological driving 'events', with the landslide effect dominating the upper 15-16 km and channel operations (straightening and extraction) dominating the lower reaches. To isolate the landslide effects we therefore looked at the increases in bedload and changes in bed levels for scenarios with and without the landslide sediment feed. By comparing simulations of the Waipa from 1993 (i.e. the year of the landslide) to 2105 with and without the effect of landslide sediment from the Tunawaea it is possible to separate out past and future change resulting from the landslide. Figure 4-19 shows the additional accumulated bedload transport in the Waipa resulting from the Tunawaea Landslide, and Figure 4-20 shows the effect on bed levels.

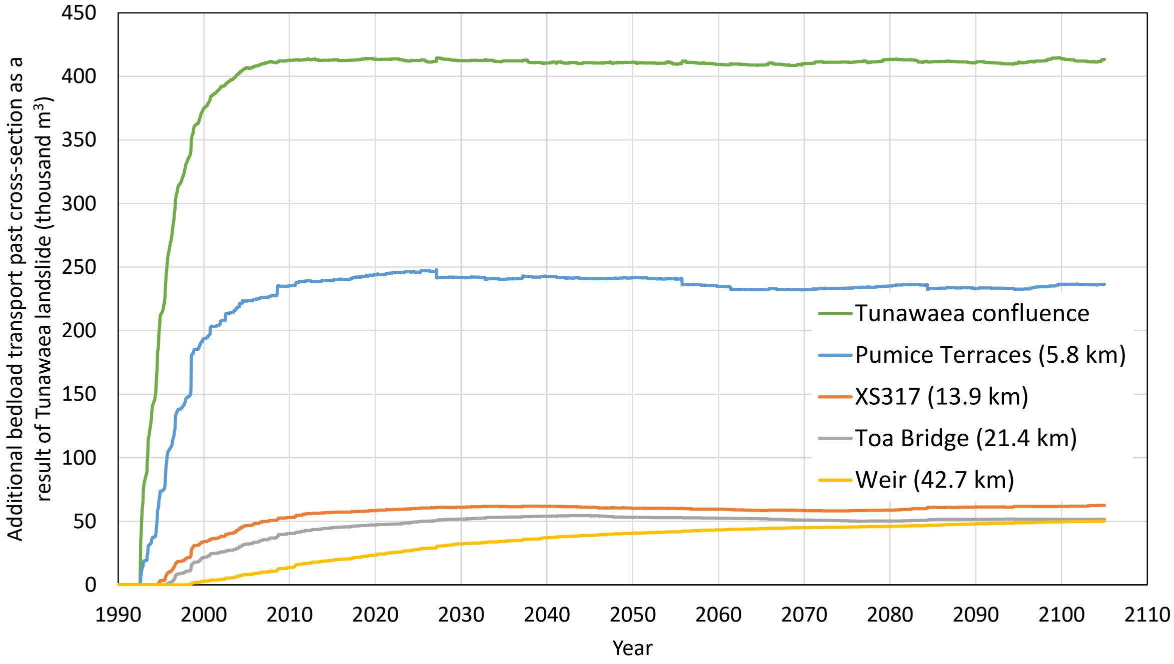

Figure 4-19: Cumulative time-series of additional bedload transported past different locations along the Waipa as a result of the Tunawaea Landslide. The lines show the additional volume of bed material which has been moved past each location. The slope of each line indicates the increase in bedload transport rate at a location as a result of the landslide, i.e. a steep gradient indicates where and when there is a high additional bedload and a flat gradient indicates no change in the transport rate due to the landslide.

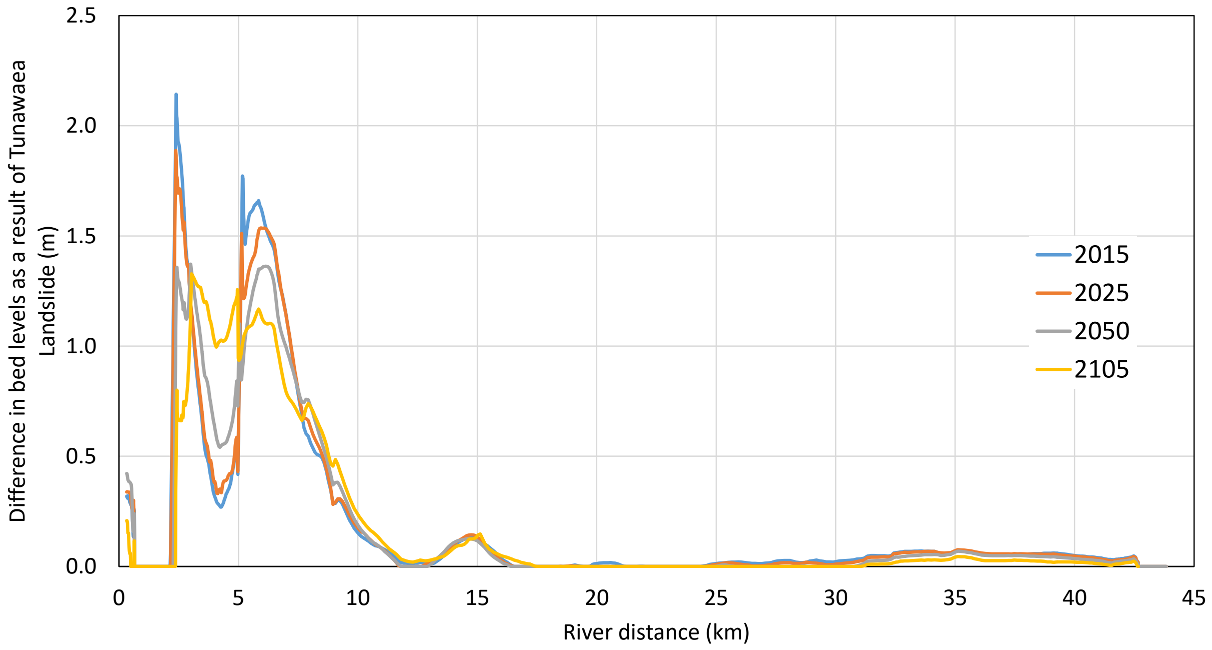

Figure 4-20: Current and future bed level effects of the Tunawaea Landslide.

The model predictions of bedload transport rate (Figure 4-19) show advection and diffusion of the landslide effects whereby as time progresses the effect on bedload moves downstream, reduces in magnitude, and extends over a longer duration. The results show that by 2015 the landslide has had a large effect on the upstream part of the modelled reach with additional bedload transport of 240,000 m^3 of sediment past the pumice terraces. Approximately 175,000 m^3 of the 420,000 m^3 of landslide derived gravel is stored between the Tunawaea confluence and the pumice terraces, with another 175,000 m^3 stored in the lower pumice terrace reach and partly confined reach (abrasion losses in the model were negligible). This results in increased bed levels of up to 2 m over the reach from 2.5 to 11 km (Figure 4-20).

The model simulation of past and future effects shows that most of the changes in response to the landslide have already occurred. Residual changes predicted are largely confined to redistribution and a slow re-working of the landslide gravel deposits in the reach downstream of the gorge from 2.5 km to 8 km. Slightly elevated transport rates continue in the lower reaches but have little effect on bed levels. Overall, the landslide has little effect on bed levels downstream of about 16 km (up to approximately 0.1 m) and this effect has largely taken place by 2015. In other words, as at 2015, the landslide has by-and-large 'done its dash'.

4.4.2 Other future morphological changes

Simulated bed level change between 2015 and 2105 in the reach downstream of the main effects of the landslide (but including the landslide in the simulation) are shown in Figure 4-21. The model predictions can be clearly divided into three separate sub-reaches:

- From 15 to 31 km: The bed levels in this reach continue to degrade, although at a slightly reducing rate over time.
- From 31 km to the Otorohanga Weir (42.7 km): Bed levels continue to aggrade, although at a reducing rate over time.

- Downstream of the Otorohanga Weir: The model suggests continuing degradation of this reach although the model results are highly uncertain in this reach as it does not extent far enough downstream to represent this reach well.

As discussed in the following section, the morphological behaviour of this lower reach appears to be dominated by the legacy of past channel engineering works and gravel extraction.

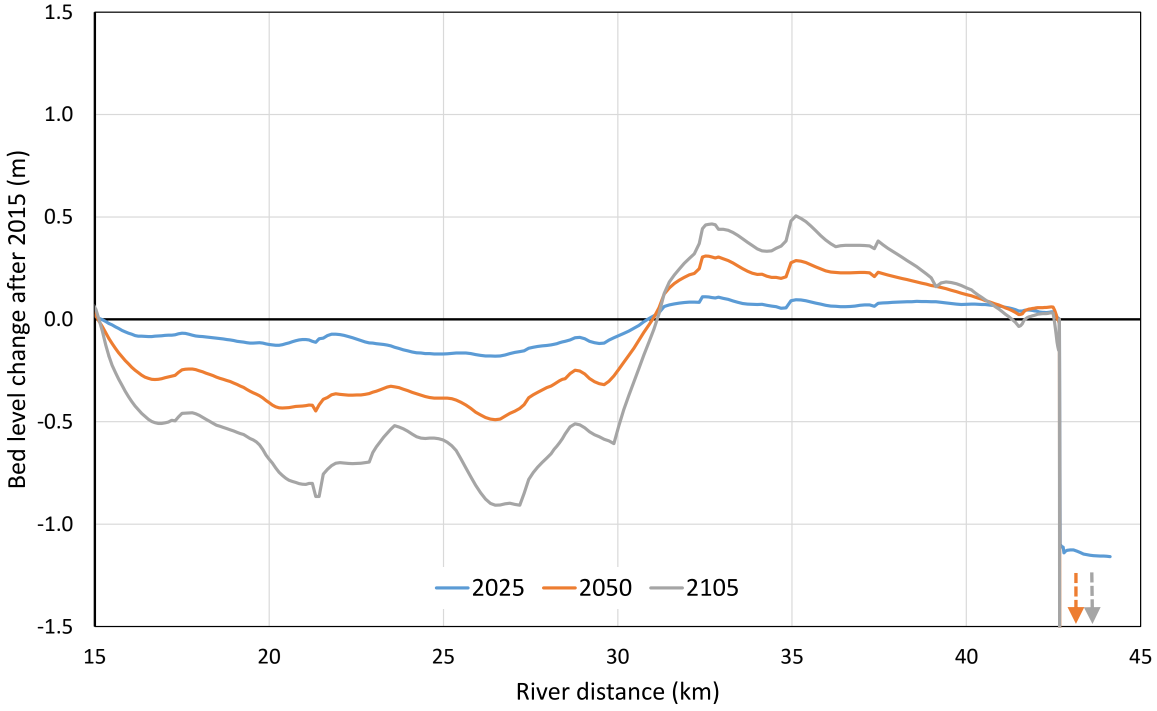

Figure 4-21: Model predictions of future bed level change downstream of the landslide influenced reach of the Waipa. Plot shows predicted bed level change after January 2015.

5 Discussion

By combining the results of the aerial photo and bed level change analysis with the modelling it is possible to draw a number of conclusions about the changes occurring in the study reach of the Waipa River. Overall it's clear that the study reach has been subject to two key morphological driving 'events', with the landslide effect dominating the upper 15-16 km and channel operations (straightening and extraction) dominating the lower reaches.

When the Tunawaea Landslide dam failed in February 1992, large volumes of bed material were released into the river system. Initially much of this was stored in the Lower Tunawaea, with gravel deposits in the valley from the landslide to the Waipa Confluence peaking at about 20 m thick 8 days after the dam failure. Subsequently ongoing bedload transport has re-worked much of this stored gravel and moved it into the Waipa.

In the Waipa the landslide derived gravel moved rapidly through the gorge reach below the Tunawaea confluence. Some temporary build-up of gravel was observed in this reach in the year following the landslide but it rapidly cleared itself. In the reach downstream of the gorge large amounts of gravel were deposited, causing the channel to become more braided. Gravel build-up drowned out the short pinched reach at 5 km and also built-up the bed beside the pumice terraces downstream, causing rapid erosion of these terraces. Bank erosion of the approximately 20 m deep pumice terraces released huge volumes of fine, low density sediment into the Waipa but most of this would have been transported rapidly through the system in suspension so it had little long-lasting effect on bed levels. River engineering works have been effective at reinstating the channel position in the pumice terrace reach and preventing further bank erosion. The current limit of bed aggradation caused by the landslide is around 16 km.

Reducing gravel inputs from the Tunawaea have allowed re-working of most of the stored gravel in the Waipa near the confluence with the Tunawaea and in the gorge reach downstream of the confluence. In the reaches below the gorge re-working is taking place gradually and the channel has largely reverted from a braided aggrading channel to a single thread incising channel. This process has been aided by natural and engineered riparian planting and other river engineering works. The reduced sediment supply has assisted in stopping lateral erosion of the pumice terrace reach and this reach is showing signs of starting to slowly incise.

Model predictions of the landslide effects match well with anecdotal information and aerial photography so we have good confidence in the capability of the model to give useful predictions of future changes. The model results show that significant volumes of landslide derived sediment (approximately 350,000 m^3) are currently stored in the reach of the Waipa below the gorge from 2.5 to 16 km but that this sediment is no longer advecting through the system as a pulse but is reasonably stable and is only slowly diffusing through the lower parts of the study reach with little effect on bed levels (less than 0.1 m).

Overall it appears that the main changes in the Waipa River caused by the Tunawaea Landslide have largely stabilised with future changes resulting from the landslide not expected to cause significant problems. The exception to this would be if a further landslide were to occur causing additional sediment to enter the system. This would not be unexpected as previous landslides are known to have occurred in the Waipa system prior to the 1991 Tunawaea Landslide, the most recent one before then occurring in 1985 (Parkin et al 1993). During surveying of bed levels at the base of the Tunawaea Landslide it was observed that Tunawaea Stream continues to erode the toe of the landslide deposit, steepening the slope face and increasing the likelihood of further failure. At one location the landslide toe had eroded 18 m between when an aerial photograph was taken in April 2012 (Google Earth) and our survey in July 2014. Figure 5-1 shows a photograph of active bank erosion steepening the toe of the landslide deposit.

Figure 5-1: Active bank erosion at the toe of Tunawaea Landslide, July 2014. Photograph looking upstream on the Tunawaea Stream approximately 750m from the Waipa confluence.

Downstream of the reaches affected by the landslide the Waipa bed levels are continuing to respond to the effects of historic river channel works. In the early bed level surveys the effects of gravel extraction are clearly evident with widespread lowering of the bed by 1 to 1.5 m from 1958 to 1978-79 in the reach from 33 km to the Otorohanga Weir. Since 1978-79 the widespread degradation has reduced and the dominant pattern of bed level changes upstream of the weir seem to be in response to a meander cut-off at 30 km (just downstream of Rendall’s Bridge) prior to 1983. The meander cut-off has shortened the river path by approximately 800 m, locally steepening the channel and resulting in headward erosion and downstream deposition. Since 1985 bed levels upstream have degraded by over 1 m and bed levels downstream have aggraded by a similar amount. The historic effect of the meander cut-off on bed levels extends over a 13 km length of channel from 25 to 38 km.

The model reproduces the effect of the meander cut-off on bed levels well and shows it continuing into the future (Figure 4-21). Model predictions of future bed level change show the effect of the meander cut-off extending over a longer reach, from 15 to 40 km, but at slowly reducing rates as bed levels trend towards a new equilibrium. The model predicts future erosion centred around 25 km of

0.5 m by 2050 and 0.9 m by 2105. It predicts deposition centred at 35 km of 0.3 m by 2050 and 0.5 m by 2105.

Downstream of the meander cut-off the main influence on historic and future bed levels is the Otorohanga Weir. The weir is effectively fulfilling its purpose of controlling bed levels at the location of the water treatment works intake. At this location, immediately upstream of the weir, historic bed levels have been stable since 1987 and modelled future bed levels are stable as well. It is likely that the weir may be exacerbating downstream erosion, but it is not possible to fully explore this in the current study as the model only extends less than 2 km downstream of the weir and should not be considered reliable for this reach.

6 Conclusions and Recommendations

Analysis of historic aerial imagery and cross-sections coupled with 1D morphological modelling has allowed a good understanding of past and future morphological changes and their causes in the study reach of the Waipa from the Tunawaea confluence to the Otorohanga Weir. These changes include:

- Gravel from the Tunawaea Landslide entering the river system following the landslide dam break in 1992. This gravel moved quickly through the gorge reach and raised bed levels significantly in the reach downstream as far as the partly confined reach upstream of the Rewarewa access point.
- Erosion of the pumice terraces caused by aggradation resulting from the Tunawaea Landslide raising the channel to the point it could erode laterally into the terrace material. This has since been controlled by engineering works.
- Ongoing gradual re-working of Tunawaea Landslide gravel deposits, but with little future effects on downstream bed levels predicted to occur through to 2105 (up to 0.1 m).
- Ongoing degradation from upstream of Toa Bridge to Rendall's Bridge caused by a historic meander cut-off just downstream of the location of Rendall's Bridge and probably also gravel extraction.
- Ongoing aggradation from Rendall's Bridge to 1-2 km upstream of the Otorohanga Weir as a result of the erosion associated with same meander cut-off.
- Stable bed levels immediately upstream of the Otorohanga Weir.
- Possible ongoing degradation downstream of the Otorohanga Weir, although this is beyond the study area limit and model results are uncertain for this location.

These reaches are shown in Figure 6-1.

Overall, the effects of the Tunawaea Landslide on the Waipa seem to have stabilised and the model predictions of future change show that future problematic bed level changes as a result of the landslide are unlikely. It should be remembered, however, that similar landslide events have occurred prior to the 1991 Tunawaea Landslide and are likely to occur again in the future.

The main predicted future changes in the study reach which could be a cause of concern are ongoing erosion from upstream of Toa Bridge to Rendall's Bridge and deposition from Rendall's bridge down to 1-2 km upstream of Otorohanga Weir. Peak erosion of 0.5 m and deposition of 0.3 m compared to current mean active channel bed levels are predicted in these reaches by 2050, with 0.9 m erosion and 0.5 m deposition predicted by 2105.

It is recommended that council staff review the predicted bed level changes to consider the likely effects on flood risk and bank stability to identify any areas where the predicted future changes are likely to cause significant problems. Ongoing monitoring of bed levels via cross-section surveys should continue on a regular basis with more frequent monitoring (5 yearly or more frequent) at areas of concern and as a minimum 10 yearly over the full study reach. Cross-section surveys should be analysed to extract information of mean bed level change as well as any significant cross-section shape changes. There would be some value in extending the modelling and analysis carried out for this study further downstream to better look at degradation downstream of the Otorohanga Weir and predict future trends in bed levels for this reach.

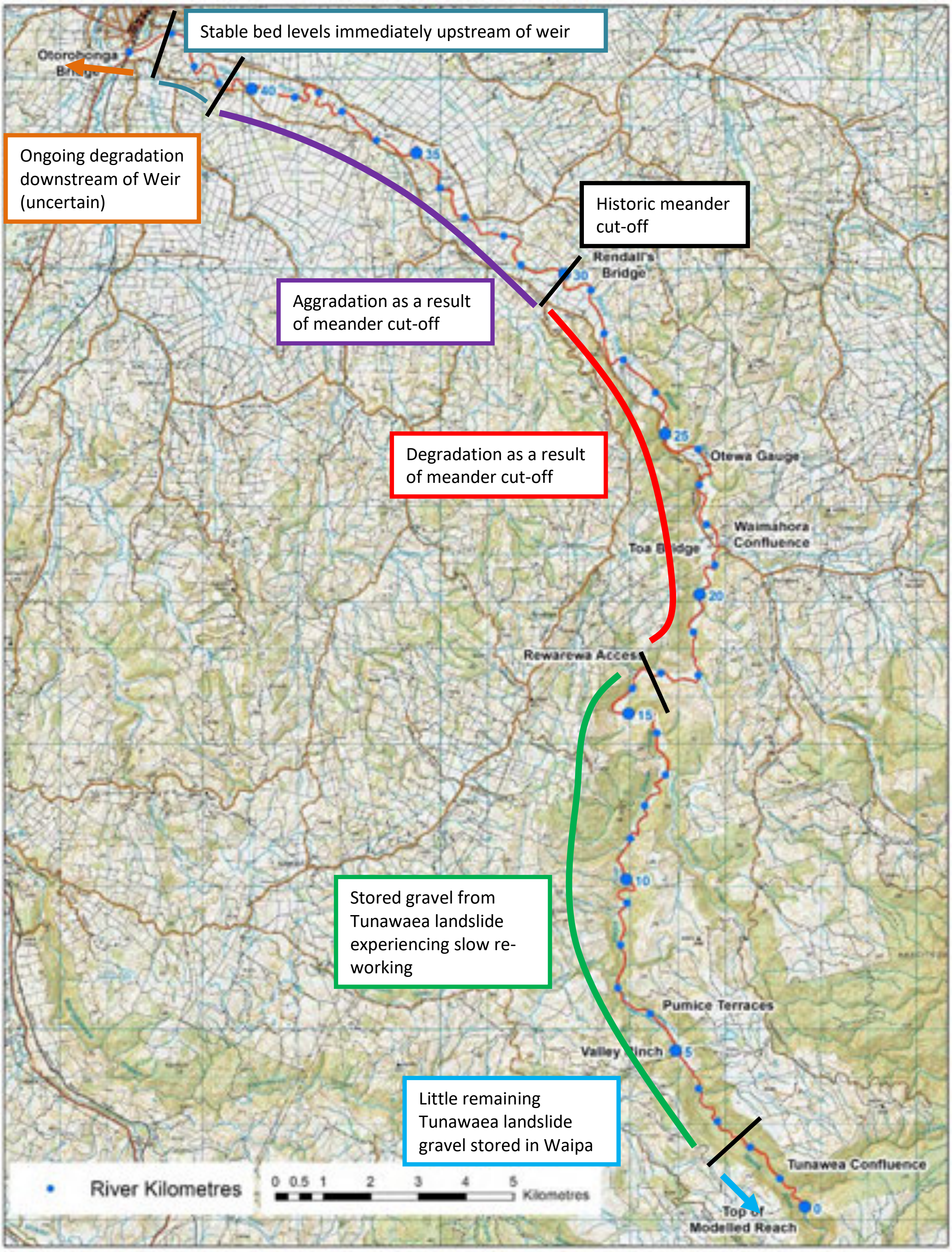

Figure 6-1: **Map of reaches qualitatively summarising predicted future changes in bed level.**

7 Acknowledgements

NIWA would like to acknowledge all the land owners and property managers along the Waipa River who allowed us access to the river to carry out the field work required from this project. The authors would also like to acknowledge colleagues Julian Sykes and Antoine Chiaverini for their help in collecting field data, and Murray Hicks for his advice and input throughout the project.

8 References

Discovery Marine Ltd. (2008) Report of survey, GPS survey of Waipa River, cross sections – Phase III. *Report Prepared for Environment Waikato*. Contract No. RCS 2006/07-51.

Discovery Marine Ltd. (2011) Waipa River – Otorohanga Weir Erosion Site Survey, 3 February 2011.

Hicks, D.M., Mason, P.D. (1998) Roughness characteristics of New Zealand Rivers. *National Institute of Water and Atmospheric Research Ltd*. Water Resources Publications.

Hoyle, J., Bind, J. (2013) Upper Waipa River survey: Data report. Prepared for Waikato Regional Council. *NIWA Client Report* CHC2013-108.

Hoyle, J., Chiaverini, A., Measures, R. (2014) Waipa morphological modelling study, Phase 2: Sediment data report. Prepared for Waikato Regional Council. *NIWA Client Report* CHC2014-105.

Jennings, D.N., Webby, M.G., Parkin, D.T. (1993) Tunawaea Landslip Dam: Part 2 – Hazard Assessment. In: *Proceedings of IPENZ Annual Conference* 1993, Hamilton. 649-659.

Parkin, D.T., Jennings, D.N., Webby, M.G. (1993) Tunawaea landslip dam: Part 1- Hazard management issues. In: *Proceedings of IPENZ Annual Conference* 1993, Hamilton. 649-659.

Riley, P.B., Meredith, A.S., Lilley, P.B. (1993) Tunawaea landslip dam collapse, physical and environmental consequences. In: *Proceedings of IPENZ conference Hamilton* 1993, Hamilton. 629-639.

Toro-Escobar, C.M., Paola, C., Parker, G. (1996) Transfer function for the deposition of poorly sorted gravel in response to streambed aggradation. *Journal of Hydraulic Research* 34(1): 35–53.

Walsh, J. 2010. GRATE V1.40 Technical Reference Manual. *NIWA Internal Report*. pp 89. Project CF105225.

Webby, M.G., Jennings, D.N. (1994) Analysis of dam break flood caused by failure of Tunawaea landslip dam. In: *Proceedings of I.E. Aust. Conference on Hydraulics in Civil Engineering*, Brisbane, Australia: 163-168.

Appendix A Cross section surveys over time

	XS	River Distance (m)	1958	1962	1963	1971	1978	1979	1985	1986	1987	1989	1990	1999	2002	2007/ 2008	2013
u/s Tunawaea	327	474															y
d/s Tunawaea	326	658															y
mid gorge	325												Not surveyed could not access				n
d/s gorge	324	3022															y
	323	3810															y
u/s pumice terraces	322	4924														y	y
d/s pumice terraces	321	5846														y	y
	320_1	7654															y
	320A	6684															y
	320	7925														y	y
	319	8976														y	y
	318A	10356															y
	318	11860														y	y
	317A	12821															y
	317	13896														y	y
	316A	15231															y
Rewarewa	316	16242														y	y
	315A	17302															y
	315	19086														y	y
	314A	20094													y		y

	XS	River Distance (m)	1958	1962	1963	1971	1978	1979	1985	1986	1987	1989	1990	1999	2002	2007/ 2008	2013
Toa Bridge	314	21424										y		y		y	y
	313A	22873															y
	313	23647											y	y		y	y
	312_1	25358															y
	312	25406						y				y		y		y	y
	311A	27195								y	y					y	y
	311	28094						y				y		y		y	y
	310J	28506								y	y					y	y
	310H								y	y	y					y	
	310G								y	y	y					y	
	310F								y	y	y					y	
	310E								y	y	y					y	
Rendall’s Bridge	310D	29882							y	y	y					y	y
	310C								y	y	y					y	
	310B								y	y	y					y	
	310A								y	y	y					y	
	310	30743						y	y	y	y	y		y		y	y
	309K								y	y	y					y	
	309J								y	y	y					y	
	309H								y	y	y					y	
	309G	31473							y	y	y					y	y
	309F								y	y	y					y	
	309E								y	y	y					y	

	XS	**River Distance (m)**	**1958**	**1962**	**1963**	**1971**	**1978**	**1979**	**1985**	**1986**	**1987**	**1989**	**1990**	**1999**	**2002**	**2007/ 2008**	**2013**
	309D								y	y	y					y	
	309C	32334							y	y	y					y	y
	309B								y	y	y					y	
	309A								y	y	y					y	
	309	32892	y				y		y	y	y	y		y		y	y
	308B															y	
	308A	34137														y	y
	308	34544	y				y					y		y but error		y	y
	307A	35105															y
	307	36271	y				y						y	y		y	y
	306	37397	y				y					y		y		y	y
	305	39121	y				y						y	y		y	y
	304	40154	y				y						y	y		y	y
	303	41454	y				y					y		y		y	y
u/s weir	302	42487	y	y		y						y		y		y	y
	301A															y	
	301															y	
	300A	43074														y	y
	298A															y	
	297B															y	
Otorohanga Bridge	297A	44127														y	y

Appendix B Model cross-section summary data

Section name	Chainage (m)	Form roughness	Initial condition grain size profile ID		Bedrock elevation (m)	Active width (m)	2013 Mean active bed level (m)	2013 Thalweg level (m)	Active bed level adjustment 2013 to 1990 (m)	Interpolated section spacing for following reach (m)
			Surface	Subsurface						
NIWA _XS327A_CREATED	317.00	0.0600	8	1	216.000	26.720	221.412	220.799	0.00	20
NIWA_XS327	473.97	0.0400	8	1	#N/A	26.720	218.152	217.539	0.00	20
NIWA_XS326	661.24	0.0400	8	1	213.528	79.000	216.000	213.528	0.00	15
NIWA _XS325A_CREATED	1398.43	0.1200	8	1	195.500	26.000	197.192	195.500	0.00	15
NIWA _XS325b_CREATED	2468.83	0.1000	8	1	164.000	40.000	165.213	164.000	0.00	15
NIWA_XS324	3017.32	0.0600	9	2	155.460	33.000	157.074	156.460	-0.50	20
NIWA_XS323	3811.21	0.0250	9	2	#N/A	46.000	148.743	147.891	-1.00	30
NIWA_XS322	4924.95	0.0250	9	2	137.750	45.300	139.397	137.994	-0.20	20
NIWA_XS322B_CREATED	4975.00	0.0300	9	2	137.390	32.493	138.912	137.394	0.00	20
NIWA_XS322_REPLICATE	5250.00	0.0250	9	2	133.500	45.300	135.661	133.994	-0.45	35
NIWA_XS321	5845.73	0.0150	9	2	#N/A	56.960	131.960	131.090	-2.00	50
NIWA_XS320A	6690.91	0.0150	9	2	#N/A	57.028	127.088	126.411	-2.00	75
NIWA_XS320_1	7653.50	0.0150	9	2	#N/A	34.400	122.158	121.690	-1.22	100
NIWA_XS320	7924.53	0.0150	9	2	#N/A	50.553	121.292	120.600	-1.00	100
NIWA_XS319	8959.01	0.0150	10	3	#N/A	77.318	116.926	116.169	-0.35	100
NIWA_XS318A	10348.06	0.0150	10	3	#N/A	56.936	111.898	110.842	0.00	100
NIWA_XS318	11814.63	0.0150	10	3	#N/A	33.074	106.463	105.708	0.00	100
NIWA_XS317A	12810.06	0.0150	10	3	#N/A	28.130	103.318	103.018	0.00	100
NIWA_XS317	13900.73	0.0150	10	3	#N/A	37.763	100.145	99.542	0.00	100
NIWA_XS316A	15218.75	0.0150	10	3	#N/A	58.538	97.181	96.331	0.00	100
NIWA_XS316	16246.91	0.0150	10	3	#N/A	47.439	94.154	92.874	0.00	100

Section name	Chainage (m)	Form roughness	Initial condition grain size profile ID		Bedrock elevation	Active width (m)	2013 Mean active bed	2013 Thalweg	Active bed level adjustment 2013	Interpolated section spacing for
NIWA_XS315A	17302.04	0.0150	10	3	#N/A	50.488	91.338	90.603	0.00	100
NIWA_XS315	19082.81	0.0150	11	4	#N/A	47.529	87.472	85.774	0.00	100
NIWA_XS314A	20094.77	0.0150	11	4	#N/A	67.543	85.439	83.793	-0.19	100
NIWA_XS314	21434.37	0.0150	11	4	#N/A	28.530	81.268	80.527	-0.45	120
NIWA_XS313A	22871.49	0.0150	11	4	#N/A	31.391	77.295	76.483	-0.20	120
NIWA_XS313	23597.44	0.0150	11	4	#N/A	53.577	75.545	74.691	-0.07	130
NIWA_XS312_1	25365.18	0.0150	11	4	#N/A	54.468	72.089	70.777	-0.14	150
NIWA_XS311A	27187.65	0.0150	11	4	#N/A	28.429	66.659	66.073	0.48	150
NIWA_XS311	28090.42	0.0150	11	4	#N/A	38.073	64.884	63.355	0.78	100
NIWA_XS310J	28493.65	0.0150	11	4	#N/A	53.866	64.273	63.262	0.57	150
NIWA_XS310D	29889.39	0.0150	11	4	#N/A	26.742	59.552	58.596	-0.16	150
NIWA_XS310	30746.97	0.0150	11	4	#N/A	39.809	57.280	56.687	-0.61	150
NIWA_XS309G	31478.44	0.0150	11	4	#N/A	52.175	55.259	54.093	-0.59	150
NIWA_XS309C	32338.58	0.0150	11	4	#N/A	47.588	52.548	52.089	-0.56	100
NIWA_XS309	32886.88	0.0150	11	4	#N/A	39.090	51.211	49.365	-0.54	150
NIWA_XS308A	34140.55	0.0150	11	4	#N/A	24.421	47.354	46.093	-1.01	150
NIWA_XS308	34543.83	0.0150	11	4	#N/A	27.467	46.573	45.657	-1.16	150
NIWA_XS307A	35108.83	0.0150	11	4	#N/A	30.712	45.441	42.730	-0.94	150
NIWA_XS307	36251.47	0.0150	11	4	#N/A	22.520	42.834	42.111	-0.51	150
NIWA_XS306real	37361.64	0.0150	11	4	#N/A	23.712	40.914	40.203	-0.08	150
NIWA_XS306changed	37468.88	0.0150	11	4	#N/A	26.353	40.972	39.607	-0.08	150
NIWA_XS305	39127.95	0.0150	11	4	#N/A	21.393	37.466	36.240	-0.05	150
NIWA_XS304	40147.27	0.0150	11	4	#N/A	28.792	36.475	35.277	-0.04	100
NIWA_XS303	41505.45	0.0150	11	4	#N/A	23.915	33.642	32.714	-0.31	50

Section name	Chainage (m)	Form roughness	Initial condition grain size profile ID		Bedrock elevation	Active width (m)	2013 Mean active bed	2013 Thalweg	Active bed level adjustment 2013	Interpolated section spacing for
NIWA_XS302	42483.61	0.0150	11	4	#N/A	28.438	32.916	31.076	-0.29	25
Weir	42669.97	0.0300	11	4	32.540	25.500	32.852	32.540	0.00	25
NIWA _XS300A_CREATED	42800.00	0.0150	11	4	#N/A	21.549	31.049	30.497	1.30	50
NIWA_XS300A	43072.66	0.0150	11	4	#N/A	21.549	30.746	30.197	1.30	100
NIWA_XS297A	44123.57	0.0150	11	4	#N/A	21.874	29.410	28.881	1.30	0

Appendix C Model grain size profiles

Profile ID	**1**	**2**	**3**	**4**	**5**	**7**	**8**	**9**	**10**	**11**	**12**
Type	**Sub-surface & feed**	**Sub-surface**	**Sub-surface**	**Sub-surface**	**Sub-surface & feed**	**Feed**	**Surface**	**Surface**	**Surface**	**Surface**	**Surface**
Size (mm)	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**	**% finer**
0.063	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.125	0.23	0.89	0.57	0.57	0.77	0.47	0.00	0.00	0.00	0.00	0.00
0.250	0.35	1.98	1.39	1.39	1.79	1.16	0.00	0.00	0.00	0.00	0.00
0.500	0.48	4.65	4.28	4.28	4.50	3.95	0.00	0.00	0.00	0.00	0.00
1.000	0.62	6.81	9.80	9.80	9.69	8.78	0.00	0.00	0.00	0.00	0.00
2.000	0.85	7.58	15.87	15.87	16.38	13.09	3.92	0.00	3.47	4.47	0.93
2.800	1.30	8.41	20.73	20.73	20.46	16.19	3.92	0.00	3.47	4.57	0.93
4.000	1.75	9.24	25.60	25.60	24.53	19.28	4.90	0.00	4.45	5.45	1.87
5.700	3.70	11.80	33.07	33.07	29.48	23.44	7.35	1.29	6.41	8.44	3.74
8.000	5.64	14.36	40.53	40.53	34.43	27.60	10.78	3.23	10.84	16.97	6.54
11.300	11.53	19.87	51.08	51.08	41.88	34.06	12.75	11.04	17.25	28.52	19.63
16.000	17.42	25.38	61.62	61.62	49.33	40.53	17.68	29.28	30.08	48.40	27.10
22.627	23.91	32.16	71.92	71.92	57.61	49.31	30.97	43.99	42.40	68.92	38.32
32.000	37.65	42.88	84.90	84.90	67.97	62.35	42.81	58.60	59.63	86.90	48.60
45.255	52.43	55.66	95.00	95.00	79.66	77.00	59.08	71.61	72.43	96.26	59.81
64.000	66.68	70.41	99.02	99.02	89.04	90.31	75.86	85.22	90.64	99.51	65.42
90.510	80.98	82.95	100.00	100.00	96.04	97.60	84.76	96.82	98.03	99.90	71.96
128.000	90.53	93.21	100.00	100.00	97.20	98.63	90.67	99.12	100.00	100.00	77.57
181.019	95.90	100.00	100.00	100.00	97.20	100.00	95.10	100.00	100.00	100.00	85.05
256.000	100.00	100.00	100.00	100.00	100.00	100.00	96.57	100.00	100.00	100.00	91.59
362.000	100.00	100.00	100.00	100.00	100.00	100.00	99.02	100.00	100.00	100.00	94.39
512.000	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Appendix D Model input parameters

Keyword	Description	Value
TS	Start time	1/1/1990 00:00
TE	End time	1/1/2105 00:00
MAX_DT_QS	Maximum time step for quasi-steady simulation	1800 s
CDT	Measure of permissible BL change over each time step (time step reduced when this value is exceeded)	0.005 m
LAYER	Storage layer thickness	0.5 m
LA	Active layer thickness	0.128 m
NBS	Maximum number of storage layers excluding the active layer and including the infinitely thick bottom layer	10
PORO	Porosity of the bed sediment	0.4
NEQAL	Non-equilibrium adaptation length	200 m
DK	Ration of roughness height to surface D90 grain size (used for calculation of grain roughness)	1.5
CHI	Weighting for distribution of deposited sediment to subsurface according to the Toro-Escobar et al (1996) transfer function	0.15
N/A	Sediment density	2.65
N/A	Abrasion coefficient	0.000005

Appendix E Flood mark survey data

Flood marks were surveyed by RTK GPS on 24 July 2014 having been pegged by Russell Powell following a small flood (peak flow of 83.1 m^3/s recorded at Otewa) on 12 June 2014. Survey was calibrated to the left bank benchmark of cross-section 313. The survey was conducted in the New Zealand Transverse Mercator (NZTM) coordinate system and is relative to the Moturiki vertical Datum.

Point Name	Northing	Easting	RL	Code	Model Chainage (km)
313-LBBM	5761794	1805409	79.770	XS_End	NA
FlLvl-001	5762164	1805031	75.317	FL	24.418
FlLvl-003	5763619	1804361	70.200	FL	26.285
FlLvl-004	5764083	1803844	68.444	FL	26.996
FlLvl-005	5765023	1803332	65.235	FL	28.395
FlLvl-006	5765753	1802587	60.700	FL	29.839
ToaBrCtr	5760160	1805831	87.079	Topo	NA