Examining the geomorphic effects of the Canterbury earthquakes on the Hororata River

Research report

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Bachelor's final assignment

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Summary

Due to a large earthquake in September 2010, part of the river bed of the Hororata River locally dropped. This caused a flood because the water could not continue its way through the original channel. A farmer enlarged the original channel to encourage the water back into the river. The National Institute of Water and Atmospheric Research (NIWA) in Christchurch, New Zealand, wants to know how the river has adjusted in the period since the 2010 earthquake. Also, they want to test their morphological model GRATE, "Gravel Routing and Bed Textural Evolution model". This model will simulate the river for the period 2010-2013 and try to reproduce the adjustments. The predicted adjustments are calibrated and validated by means of fieldwork material.

There are two main research objectives:

1. *Measure how the Hororata River responded to the September 2010 earthquake and subsequent human channel modifications.*
2. *Test NIWA's 1-D model (GRATE) to see how well it predicts the measured response from goal 1.*

The main research question in this project is:

How has the Hororata River adjusted in response to the effects from the Canterbury earthquakes and can this response be properly simulated?

The following sub questions will underpin the main question:

1. *What were the direct effects of the 2010 earthquake with respect to the Hororata River?*
2. *What morphological changes are predicted by the model GRATE for the period 2010-2013?*
3. *What is the morphology of the river in 2013 and which adjustments did take place?*
4. *How well does the GRATE model predict the measured water levels and changes between 2010 and 2013?*

Around 300 meters of river bed has dropped 1.5 meters down due to an oblique down slip of the Greendale fault. This resulted locally in an increase of river bed slope of 2.3 times the average slope. According to the simulation of GRATE, only adjustments occur around the meandering bend. Validation data proved the correctness of the simulation and indeed, only changes were visible near the meandering bend. After three years, both the model run and the 2013 survey data showed that the slopes of the reach around the fault line have evened. In the humanly enlarged channel are almost no adjustments visible.

The GRATE simulation is predicting erosion and deposition in an accurate way. The simulation calculates the vertical adjustments of the river with an average deviation of 0.20 meter. There are no horizontal changes possible in GRATE (bank erosion processes are currently not well represented in this model). However, GRATE may be predicting the degree of adjustments adequately, but not the nature of the adjustment. Generally, GRATE can predict the adjustment of the river very well.

In the future the river slope will eventually be restored to levels before the earthquake. However, the speed of these adjustments and restoration depends on the farmer. Bank protection may encourage bed erosion if there is excess energy in the river that need to be dissipated. This will lead to a quicker restore of slope. If not, the river will probably continue to erode his banks and deposit sediment right after the drop in order to restore the slope of the river.

Preface

This report is submitted in partial fulfilment of the requirements for a Dutch bachelor's degree in Civil Engineering.

The report presents the research, findings and recommendations resulting from the project 'Examining the geomorphic effects of the Canterbury earthquakes on the Hororata River', carried out by the National Institute of Water and Atmospheric Research (NIWA) in Christchurch, New Zealand. The objectives were to see the response of the river to effects from a heavy earthquake and test a morphological model of NIWA and see if it can be used to predict the adjustments of the river.

It was a great experience, both working and living in New Zealand. A special thanks to my supervisors Murray Hicks and Joanna Hoyle, for giving me the opportunity to carry out the project at NIWA. Furthermore I would like to thank the other members of sediment processes, who provided me with great advice and ideas. Also, thanks to everyone who joined me on fieldwork days. I had a great time at NIWA, due to the friendly atmosphere and the good facilities.

Also, I want to thank Jan S. Ribberink, my supervisor from the University of Twente, for contributing valuable advice and feedback on my work and F.R. Bijleveld, who is acting as a second reviewer.

Christchurch, June 2013.

Michiel Pezij

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1 Introduction

New Zealand is part of the ring of fire around the Pacific Ocean, which is geologically very active. The Australian Plate and the Pacific Plate meet here, creating many faults in New Zealand. When these plates move, they cause earthquakes. At 4:35 in the morning on 4 September 2010 the region of Canterbury, New Zealand, was struck by a magnitude 7.1 earthquake. This quake caused a lot of damage in the city of Christchurch, but luckily there were no casualties (TVNZ, 2010).

The region around Christchurch, Canterbury, has had thousands of earthquakes over the past 2 years and the years before. However, most quakes are not dangerous as they are not even felt by most people. The September 2010 earthquake was the first heavy earthquake in this region since a long time. The epicenter of this earthquake was close to the town Darfield and near the Hororata River. The Hororata River is a tributary of the Selwyn River and the length of its stream is around 35 km. The river is meandering through the farmlands of Canterbury. It source lies near Mount Hutt in the Southern Alps of New Zealand. The river is mainly fed by ground water. However, it reacts quickly after rainfall, causing local floods.

A section of this meandering stream is crossed by the Greendale Fault, which ruptured during the September 2010 earthquake. By means of the earthquake, the riverbed was locally dropped and water spilled out over the left bank of the river, as can be seen in Figure 1. The black dashed line is the fault, the blue solid line represents the river. Due to the fault, the land at A was lowered. This meant that water from upstream (right side of Figure 1) could not access the original channel (top side of Figure 1) anymore. This resulted in a flood. A farmer living close to the river took immediate action and made large modifications to the channel, directing the river back into its original channel downstream of the cut-off. The downstream channel was also made larger to keep the water there. Thus, the morphology of the river changed and these changes will result in a reaction of the river, in the form of river bed adjustments.

This is confirmed by Davies & McSaveney (2011): “Further earthquake-induced flooding was caused by downthrow of one meander bend of the Hororata River, Canterbury, by about a metre (Quigley et al., 2010); this caused the river to flow into the adjacent Selwyn River in a new course across farmland. Local farmers spent large sums in deepening the reach below the meander bend to restore the river to its former course.” This section of the river is the study area of this bachelor’s final assignment. The location of the study area is shown in Figure 2. A top view can be found in Figure 4.

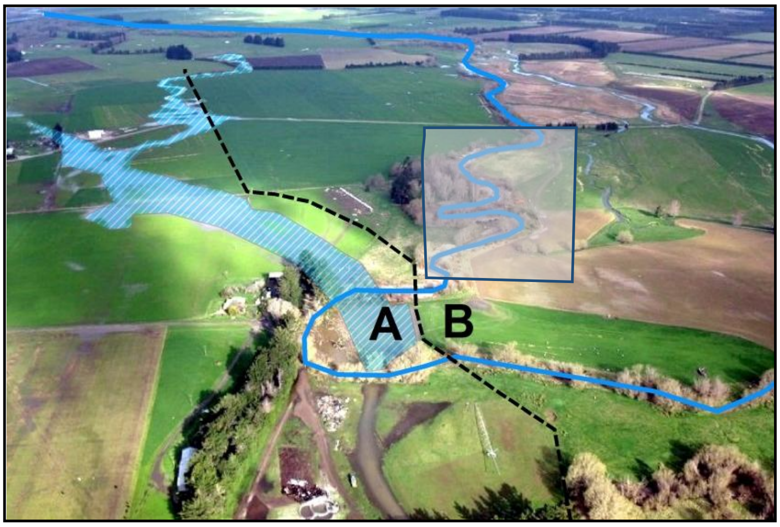

Figure 1 - Hororata River including fault, the dugout part of the river is highlighted in the grey rectangle

The basis of this report is an assignment commissioned by NIWA (National Institute of Water and Atmospheric Research) in Christchurch, New Zealand. The Hororata study is of great interest to NIWA because it is a good example of a river that has been disturbed by a large earthquake and human channel enlargement. There is not much knowledge yet about how the river responded (and continues to respond) to these disturbances. This project will be used as a case study to measure the river response. Also, the 1D morphological model GRATE (Gravel Routing and Bed Textural Evolution model) of NIWA will be validated to see if it provides an appropriate way to simulate and predict the adjustments. Directly after the quake, researchers from NIWA collected flow and topographic data in the study area. These data will be used in this project and the model. In this report, this is called the 2010 fieldwork. The author of this report also collected fieldwork data during the assignment, which is named 2013 fieldwork.

In this report, first the research motive and goals will be outlined. After that, the problem definition is highlighted. This includes a literature study to sketch a theoretical framework and a discussion of the research questions. Following the research questions, the method of research is explained. Next, the results, including a future prediction, are presented with a discussion. Finally, the report ends with a conclusion and recommendations for further research.

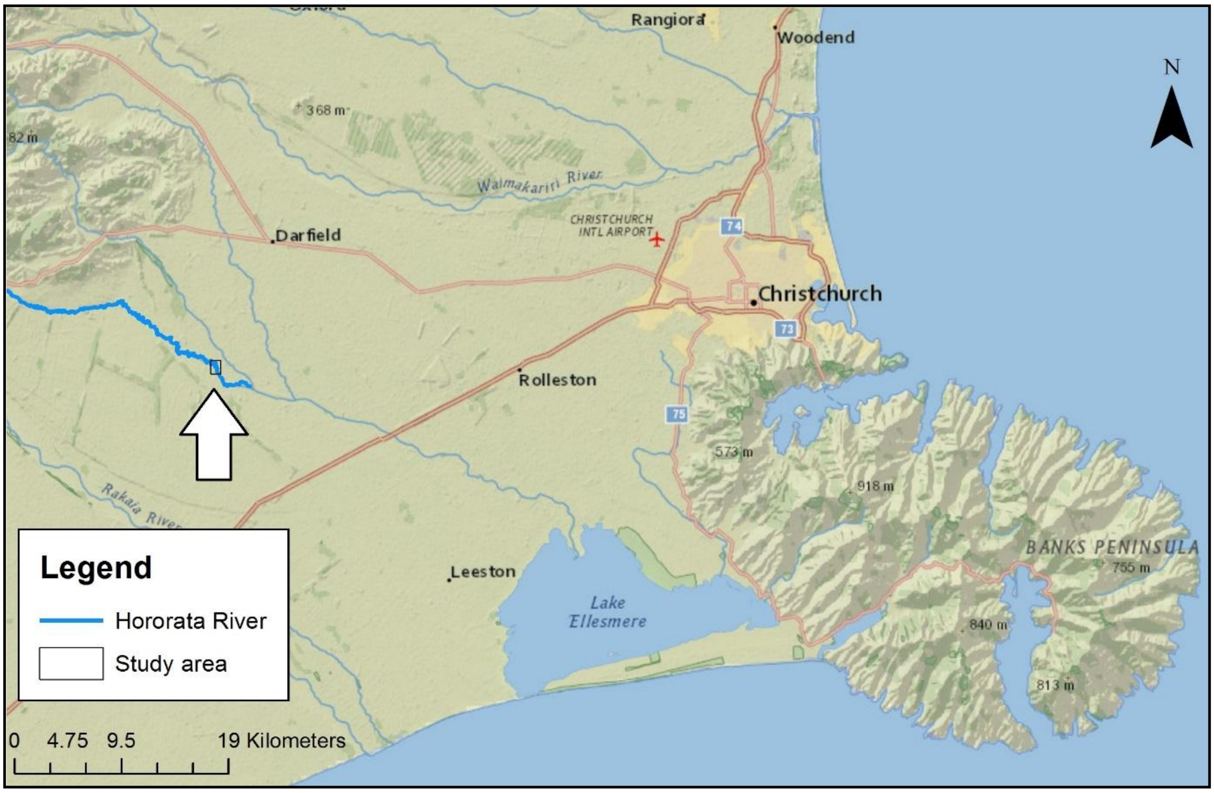

Figure 2 -Location of study area

1.1 Motive/Goals

NIWA wants to know how the river has adjusted to these two disturbances. As stated before, the Hororata project is of interest for them because it is a great example of a river that has been disturbed by a major earthquake and human channel enlargement. For me personally, it is interesting to study morphological processes. This project provides a good example of these processes. Hopefully, the results from this project contribute to the understanding of the behaviour of river systems that are adjusted by earthquakes or other natural disasters.

Hydrologic and sediment models are already reliable in many specific situations. Due to continuously development of these models, they can be used in more and more situations. This assignment is a perfect opportunity to see if the model of NIWA (GRATE) can perform well when used for predicting changes after a heavy earthquake.

So summarized, there are two main research objectives:

1. Measure how the Hororata River responded to the September 2010 earthquake and subsequent human channel modifications.
2. Test NIWA's 1-D model (GRATE) to see how well it predicts the measured response from goal 1.

1.2 Problem definition

This chapter includes the problem definition. First, a literature review is reflected to set a theoretical framework. After that, the research questions are discussed.

Theoretical background

There is already a lot of research done on the subjects of natural effects of earthquakes on rivers. Several authors agree with each other on these effects (Bradley, 2012; Cloetingh & Negendank, 2010; Cox, et al., 2012; Holden, et al., 2001). Strong ground motions, flooding and liquefaction are some examples. The Hororata River also suffered from these effects, in particular strong ground motions which locally lowered the river bed. To mitigate associated problems (e.g. flooding), human intervention is possible, to some extent. A farmer did some adjustments directly after the earthquake. However, the effects of these adjustments in the long-term are not known yet, according to Davies & McSaveney (2011). Scientists do agree that the effects of earthquakes cause a lot of trouble and damage, for example Bradley (2012) and Green & Cubrinovksi (2010). River systems can recover from these changes. However, Wallick (2004) states that this will almost always be a bad response, in the sense that this recovery is bad for the hydrological system. River adjustments take some time and therefore could have hydrological and ecological implications.

There is a chance that in the future these effects, adjustments and problems can be jointly tackled. The hydrological and sediment models are already reliable, although they must be calibrated in every different case and scenario (Chagué-Goff, et al., 2000; Cox, et al., 2012). But, it is unknown if the models that predict long-term changes are ready for such use. At the moment there is still a lot of seismic activity in the Hororata river area. Thus, the possibility of research will remain for the time being.

Concluding, there is a lot already known about adjustments of rivers like the Hororata, however more and better knowledge is needed. There are a lot of short-term problems recognized, but the morphological models need to be improved before the long-term problems can be recognized. Developments in the field of these models are expected in the coming years. So, this project provides a great opportunity to see if the morphological model of NIWA can simulate such extreme changes in a good way.

Research questions

The main question is:

How has the Hororata River adjusted in response to the effects from the Canterbury earthquakes and can this response be properly simulated?

There are several important things that need to be known in order to answer this question. First, the direct geological and hydrological effects of the 2010 earthquake with respect to the Hororata River must be clear. Also, the human interventions should be discussed. These effects contribute to the initial setup of the model. After the model run, the predicted changes must be analysed, examining which changes stand out and which are logical and which are unexpected. Possible reasons for these changes can then be discussed. Also, the fieldwork data should be analysed. If possible, the 2013 fieldwork data will be compared with the collected data and the simulation run from 2010. With this comparison, the validity of the model GRATE can be assessed in order to determine the usefulness of the model for predicting future changes in the Hororata River.

Summarized in 4 sub questions:

1. What were the direct effects of the 2010 earthquake with respect to the Hororata River?
2. What morphological changes are predicted by the model GRATE for the period 2010-2013?
3. What is the morphology of the river in 2013 and which adjustments did take place?
4. How well does the GRATE model predict the measured water levels and changes between 2010 and 2013?

Next, the research methodology is elaborated, including an explanation of the model GRATE.

2 Methodology

In order to answer the research questions a roadmap was constructed at the start of the project. The roadmap for this assignment is outlined in Figure 3.

The first step is processing the 2013 raw survey data in order to setup the GRATE model. This setup is complemented by processing 2013 raw survey data. This data, river bed material and cross section data, is collected during fieldwork in May/June 2013. After the initial setup of the model, GRATE is calibrated. The next step is running the model with the available data, which results in a prediction of river adjustments in 2013. This prediction is then compared with validation data, in order to check the appropriateness of the use of GRATE for this project.

All these steps will be discussed in this chapter. First, the surveying fieldwork is discussed. Next, the tools used for data processing are specified. Then, the model GRATE is explained, including pre- and post-processing of input- and output files and how results are interpreted.

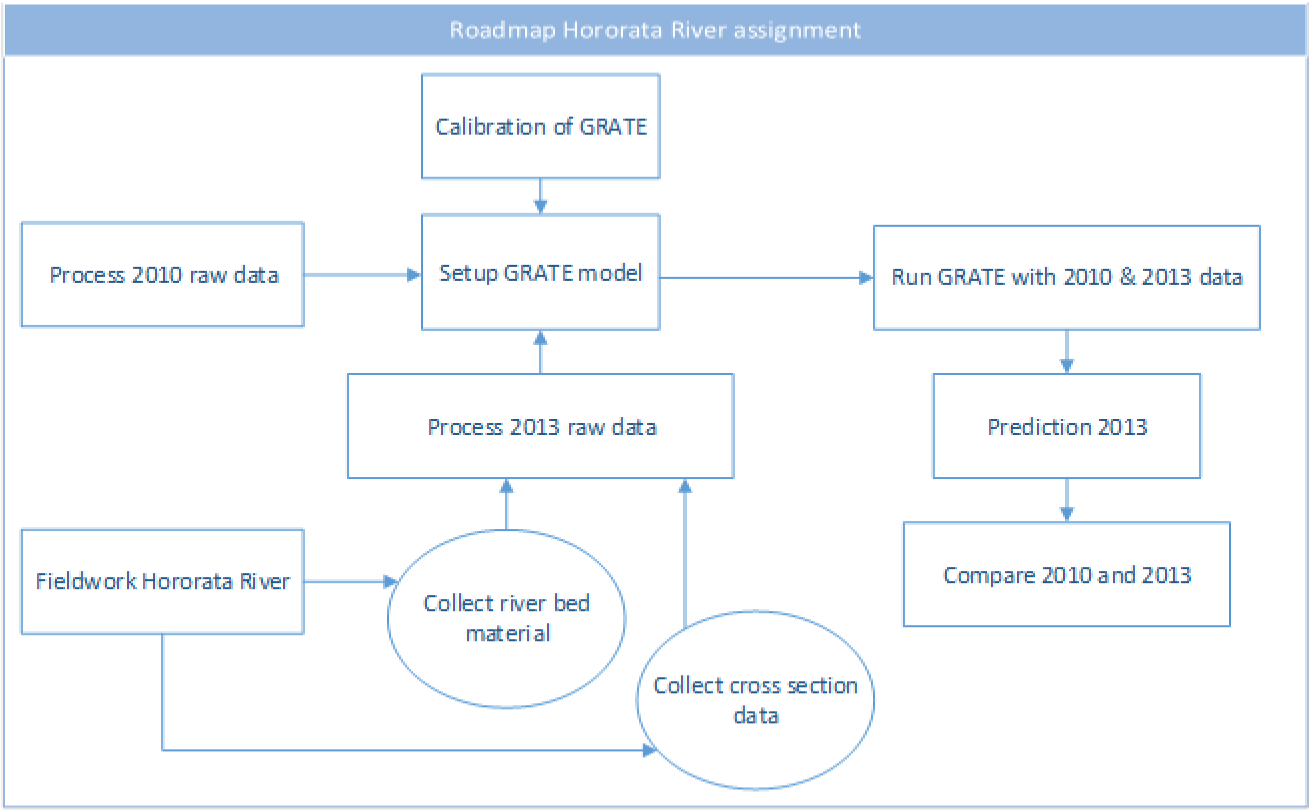

Figure 3 - Methodology

2.1 Surveying fieldwork

At the start of this assignment, survey data from directly after the earthquake (October 2010) was available. The total length of surveyed river is 2189 meters and the average distance between cross sections (XSs) is 70 meters. This raw material is processed into 35 cross section profiles of the river, which can be used as input for the morphological model (GRATE), see Figure 4. The 2013 survey would have needed to be extended upstream if the results showed that level bed changes occur as far upstream as the upstream boundary of the model. However, the 2013 fieldwork proved that this was not necessary. The 2013 fieldwork consists of resurveyed cross sections, namely 12 to 20. Due to time limits the surveying efforts focused around the area of particular interest. This area included the cross sections several hundred meters up- and downstream of the fault line. This is where the greatest changes are expected. For this reason, the 2013 survey does not cover the full 2010 study area.

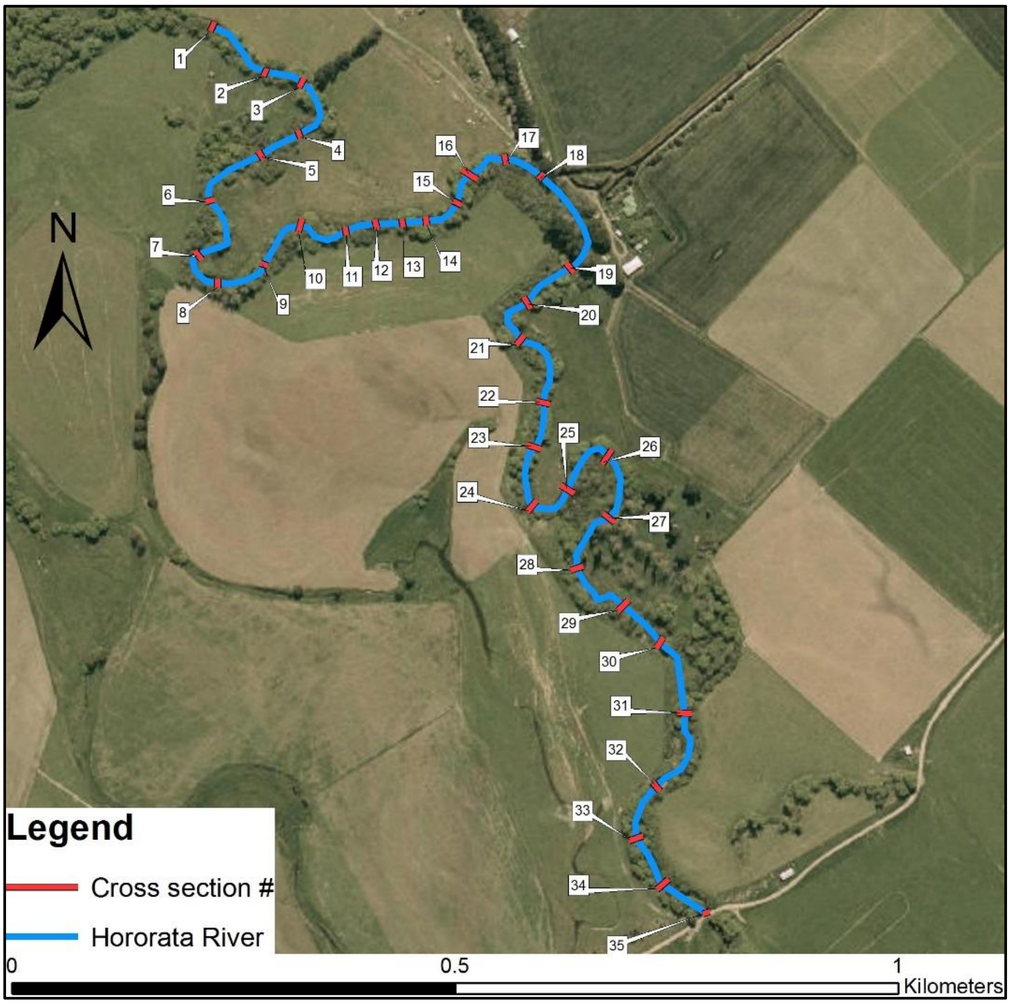

Figure 4 - Location of cross sections

Equipment used during fieldwork are the RTK-GPS, ADCP and laser level. The river bed profiles were in 2010 captured using ADCP. ADCPs measure the velocity of the water using and transmitting an acoustic pulse into the river. This pulse returns to the ADCP and the equipment can construct a cross section profile with the information gathered due to the returning pulse(Wall., Nystrom, & Litten, 2006). However, due to time limitations, this technique was not used in the 2013 survey fieldwork.

It was possible to measure the profile of a cross section with the RTK-GPS. "RTK is a highly precise technique that results in one inch pass-to-pass and year accuracy. RTK GPS requires two specialized GPS receivers and two radios. One GPS receiver is set up as a base station within a 6 mile (9.6 km) radius of the field you are working so it can send the correction message to the roving receiver. Both receivers collect extra data from the GPS satellites known as L2 Band, that enables this better precision" (Trimble Navigation Limited, 2006). RTK-GPS compensates the error due to the movement of satellites that occurs with normal GPSs.

A downside of this technique is that the signal of the RTK-GPS is very bad underneath trees. In the case that a measurements could not been done, a laser leveller was used to get the cross section data. The leveller transmits a laser horizontally. Using the laser, survey staff and tape-measure, the elevation and distance of points across a cross section can be measured relative to the first point of that cross section. These first points are pins that were placed during the 2010 fieldwork and their absolute location is known. With this knowledge, a cross section profile can be derived.

The water elevations during a discharge of 2.6 m^3/s were also measured using the RTK-GPS. Every 50 meters a measurement was done in the middle of the river. In deeper sections where it was not possible to access the middle of the river, the water elevation at both sides was measured. The average of these two was then used as the water elevation.

2.2 Data processing

The 2010 and 2013 survey data needed to be post-processed to generate input files for the model. Most of the data processing was done with Microsoft Excel. Raw survey data existed of topographic data, containing northing & easting (geographic Cartesian coordinates) and elevation data for points along the river. The input files for GRATE were created using a standardized excel macro form made by NIWA.

2.3 GRATE

GRATE is a model developed by NIWA. It is a one-dimensional morphological model that can be used to simulate reach scale channel and bed textural evolution in gravel-bed (like the Hororata River) and mixed gravel and sand bed channels. GRATE is an uncoupled non-uniform sediment model. This means that within each time step the hydraulics and sediment transport processes are solved sequentially without feedback, and that the sediment within the bed and in transport is represented by multiple size fractions, each of which is accounted for separately. At the end of each time step, cross-sections at the computational nodes are updated to reflect any change in bed elevation determined from sediment continuity considerations."(Walsh, 2013).

The structure of GRATE can be seen in Figure 5. The required input includes cross section data (river profiles), river flow data (discharge), river behaviour settings (like initial values for thickness of storage and active bed layer and initial water surface elevation approximation), sediment inflow data and grain size distributions of the river bed and subsurface. During a model run, water levels, sediment transport and the new bed elevations are stored and used for each time step. The output files include (total) sediment output, total change in bed elevation, hydraulic data (like Froude numbers) and the new cross sections profiles.

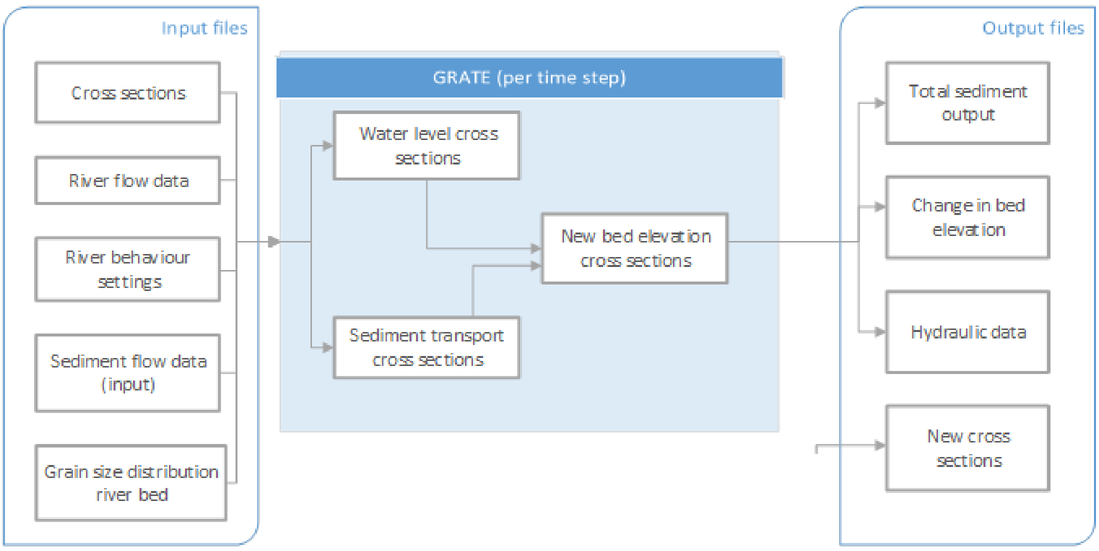

Figure 5 - Structure GRATE

The flow model of GRATE simulates both quasi-steady and unsteady flow. Due to time limitations, only the quasi-steady flow was used in this project, because the model was limited in its ability to simulate unsteady flow for this specific project. This means that no spatial or temporal variations in flow are simulated within one time step.

The river channel can be represented in GRATE in two ways: a rectangular laboratory flume or a channel with floodplains on the left and right berms. The latter representation was chosen for this project. This representation allows differences in roughness between the main river channel and the floodplains to be included. “The composite roughness for the channel is determined from the total conveyance, which is taken as the sum of the conveyance of the left berm, main channel and right berm channel segments.” (Walsh, 2013). The form roughness parameter used by GRATE is the Manning’s n coefficient, which can be used for calibration. Also, grain drag is calculated off the D_{90} of the surface layer grain size distribution, also in the form of Manning’s n. Total roughness is calculated from grain drag and form roughness.

“The GRATE sediment transport model calculates non-uniform sediment transport using either an equilibrium transport formulation, where each cross-section is assumed to be able to transport sediment at the capacity transport rate, or a non-equilibrium formulation in which the sediment transport response to equilibrium conditions is accounted for in terms of a characteristic length scale (called the non-equilibrium adaption length).”(Walsh, 2013). The equilibrium transport formulation was chosen for this project. A non-equilibrium formulation would have been preferable, because “it provides more stable and intuitively more realistic adjustments to bed morphology” (Walsh, 2013). However, it takes more time to implement this approach and for this purpose the equilibrium transport formulation was deemed adequate.

The river bed in GRATE is represented by the three-layer conceptual model: a surface/active layer that exchanges sediment with the flow, a subsurface layer underneath the surface layer and a bed-load layer consisting of sediment particles in motion. Bed-load transport capacities can be calculated by several transport formulas, the one that is used in this project is Wilcock & Crowe (2003), because this one is very suitable for gravel beds like the Hororata River (Wilcock & Crowe, 2003).

Input files

GRATE needs the following input files: river flow data, cross section data, grain size distributions of river bed and sub-surface and a sediment inflow rate (bedload feed rate).

River flow

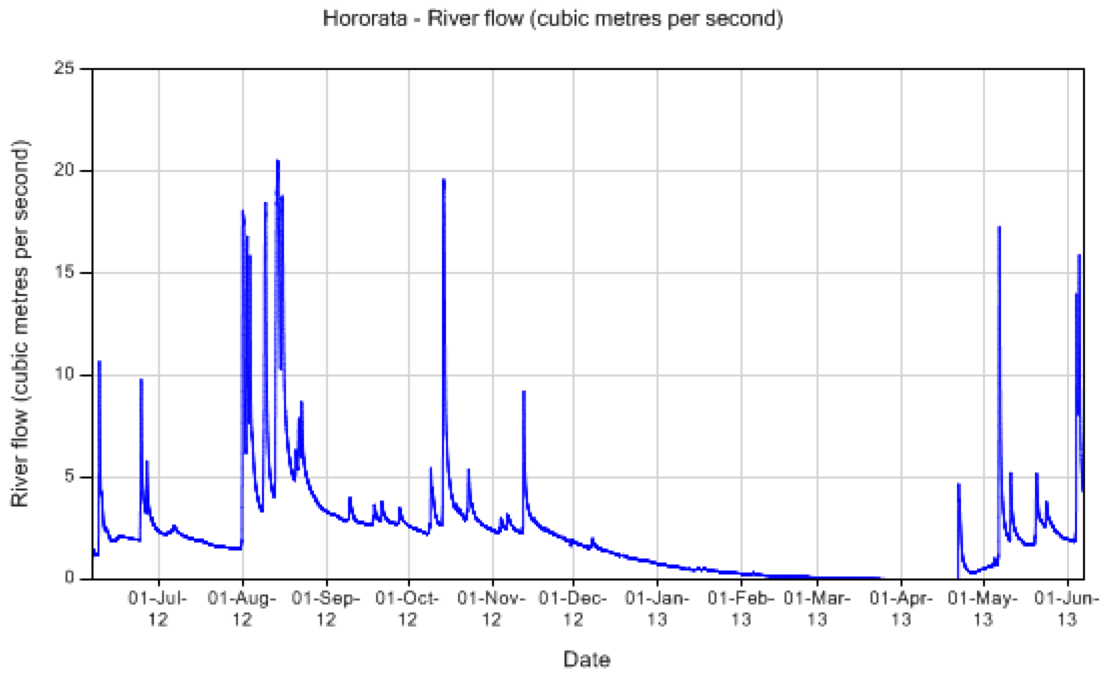

Figure 6 - Flow rates during period July 2012/June 2013

Canterbury Regional Council (previously known as Environment Canterbury) provided river flow data for the period between September 2010 and April 2013(Environment Canterbury, 2013), see Figure 6 for an example and Appendix I for the full time series. The river flow recorder is situated a kilometer upstream of the study area. This means that the flow recorder data should be consistent with the flow in the study area.

However, the flow recorder site has not been re-gauged since the September 2010 earthquake. During the 2013 fieldwork, a flow was gauged to validate the flow recorder data. The goal of the gauging was to check if the recorder data is usable. Two different flows were gauged. The results are shown in Table 1. The recorder underestimates the flow by about 5-7%. A possible explanation for this deviation is the continuing change of the river cross section at the recorder site. This knowledge is used during calibration to adjust the model properly.

Table 1 - Results gauging

River flow discharge ECAN (m^3/s) (Environment Canterbury, 2013)	River flow discharge gauging (m^3/s)	Underestimation of flow discharge
3.84	4.05	-5.47%
2.62	2.81	-7.25%
Average underestimation:		-6.36%

Cross sections

The cross section profiles in GRATE are represented as points, see Figure 7. The input cross sections consist of 2010 survey data. The active bed is distinguished from the left and right banks by flags. By doing this, GRATE will only calculate sediment transport for the active bed.

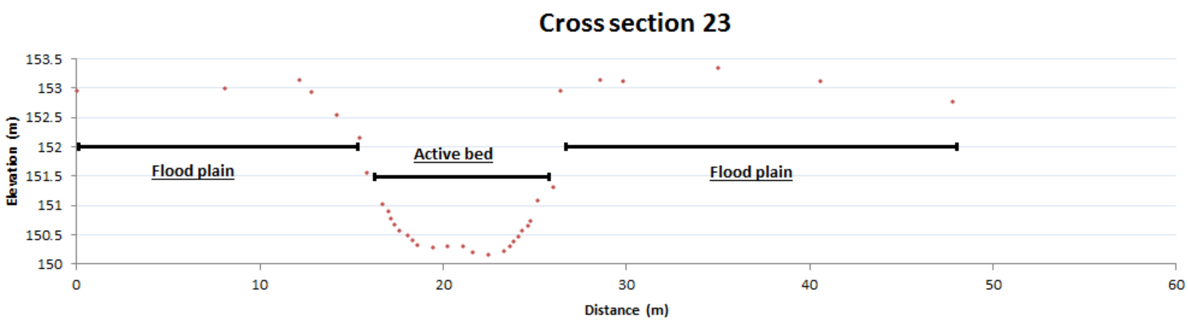

Figure 7 - Visualization of cross section

During test runs of GRATE, it became clear that the surveyed river length (x meters up- and downstream of the fault line was adequate, but the model had a lot of instabilities along the fault (between cross section 15 and 20). These instabilities were fixed by interpolating cross sections between cross section 15 and 20 to reduce the cross section spacing in the model. A macro from NIWA was used to create these interpolated cross sections.

Grain size distributions

In order to run GRATE, also bed material input data are needed. Unfortunately, no bed material data was collected during the 2010 fieldwork. This material was collected during fieldwork in 2013. For the collection of river bed material, two methods are used: Wolman grid sampling and bulk sampling. The Wolman grid sampling technique is a sampling method "that could accommodate the wide range of grain sizes present in a river bed, represent an entire river reach, and only sample surface particles"(Petrie, 1998) . The surface samples obtained are used as an input for the model. The model generates its own surface grain size distribution using this data. Seven sites were used for Wolman sampling, namely cross sections 1, 8, 12, 16, 19, 24 and 34. At least 100 random clasts were collected at each site. Wolman sampling was used to get the average grain size distribution of the river bed surface layer, the red dashed line in Figure 8. This grain size distribution is an average of the samples collected at the seven sites. These samples are presented in Appendix II. The 2013 grain size distribution are assumed to represent the 2010 distributions in an acceptable way. However, the different Wolman samples vary somewhat, so the average distribution does not cover the entire study area. The simulated values are therefore probably under- or overestimated.

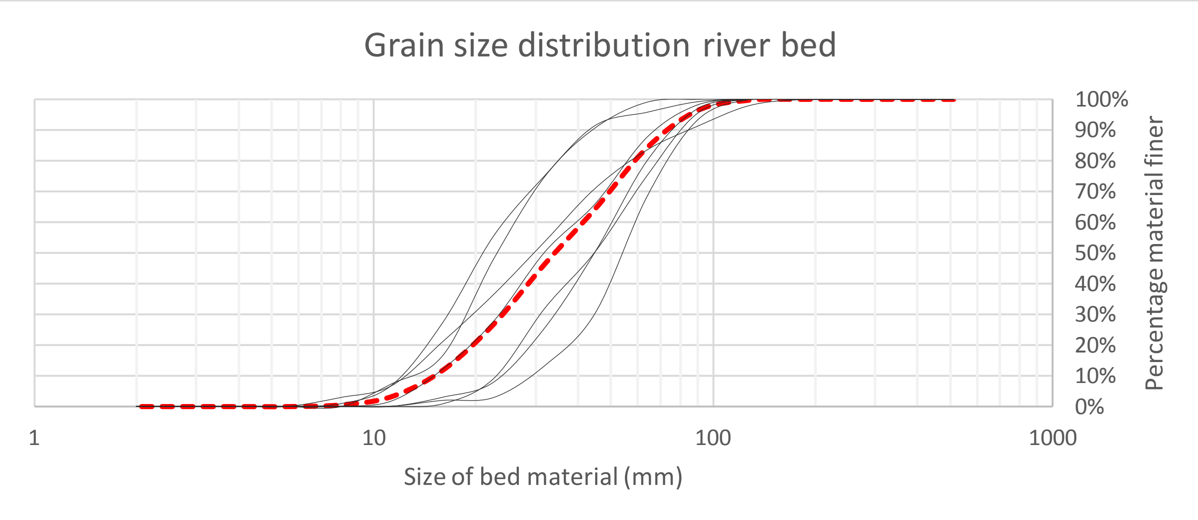

Figure 8 - River bed surface grain size distributions

Bulk sampling was used to collect material below the level of the largest surface class and from within one layer(NIWA, 2011). With this information, the average grain size distribution of the subsurface of the river was determined, the red dashed line in Figure 9. This average distribution is an average of the distributions of two samples (sediment calibration). The distribution for these specific sections can be found in Appendix II. Two sites are used for bulk sampling, namely cross section 16 and 24. Samples of at least 100 times the weight of the largest class visible on the surface layer were collected and sieved in the field. To collect information about the grain sizes smaller than 8 mm, samples were brought to NIWA to sieve them in a laboratory. This had to be done in order to get information about the smaller grain size clasts.

The Wolman samples are also used to feed the model at the upstream end. The bedload feed rate for a specific discharge was calculated with the Wilcock-Crowe formula (2003). The samples are used to extrapolate the bedload feed rate to every possible flow in the river, see Figure 10. The R^2 of the interpolated values is 0.999, which is very good. The values used for extrapolating can be found in Appendix III. These values were obtained after sediment calibration using an Excel macro of NIWA to calculate the bedload feed rate for different discharges.

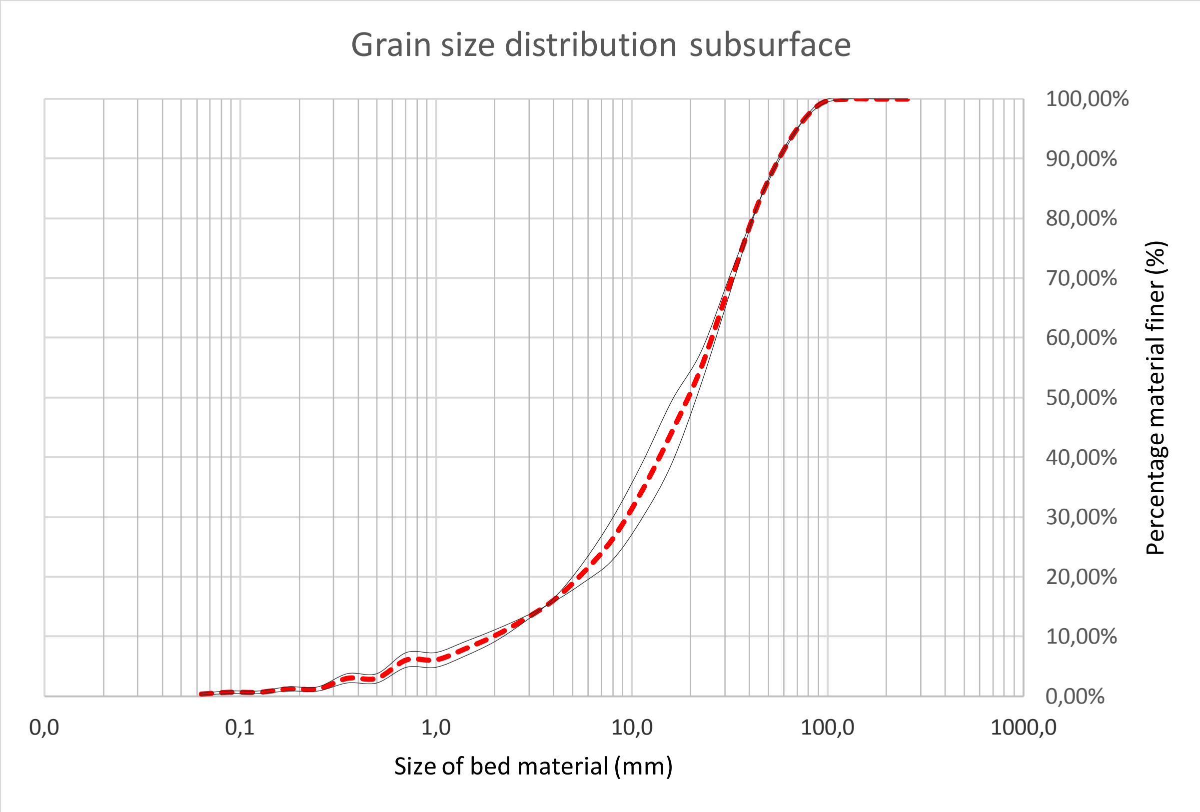

Figure 9 - River subsurface grain size distribution

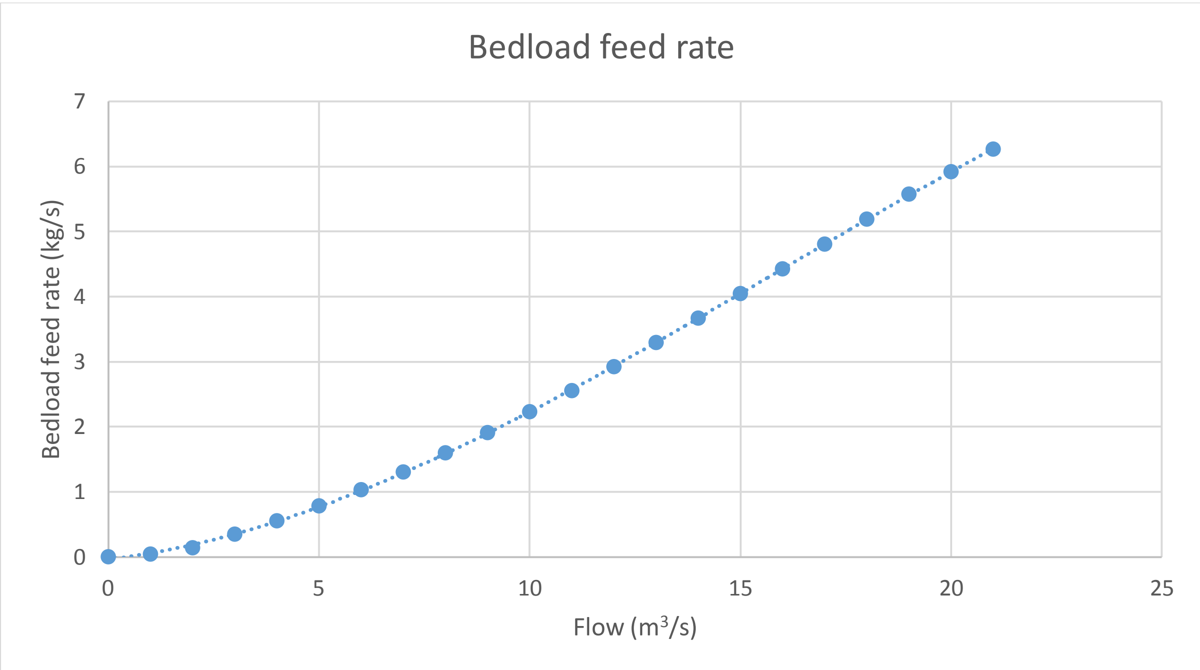

Figure 10 - Bedload feed rate

Boundary & initial conditions for GRATE

The 2010 fieldwork was done during a river discharge of around 2.6 m^3/s. To be consistent, the 2013 fieldwork was also done during a discharge of 2.6 m^3/s. The 2010 dataset contains water edge elevation data, which made it possible to calibrate the model (by adjusting Manning's n coefficient). In the initial run, a Manning's n coefficient of 0.03 was used. This is an average value for rivers similar to the Hororata when looking at the river bed composition, according to Hicks & Mason (1998). With help of literature globally values which can be used for calibration were selected(Hicks & Mason, 1998). Afterwards, every single cross section was calibrated by adjusting this Manning's n coefficient until the modelled water surface profile matched the measured water surface profile at a given steady discharge (2.6 m^3/s). All the information described in this chapter was formatted and converted to an input file for GRATE, see Appendix IV. For a comprehensive explanation of this file, see Walsh (2013).

Also, a sediment transport calibration was performed by checking how the river responds to different bedload feed rates. The model performs well using low sediment input rates from upstream, however handles large input rates not properly. The used bedload feed rate seems very low e.g. because there was no fine material found during sampling. After calibration, it was found that there might be finer material in the river bed. However, the discharge during the fieldwork was too high, disturbing the collection of samples.

Model run

The model was then run with varying discharges (using flow data from the flow recorder) over the 2010-2013 model period. The start- and end time of the model were respectively 03-07-2010 00:15:00 and 01-04-2013 00:45:00. The start time is one day before the earthquake to let the model initialize and the end time was chosen because the flow data was available up to April 1 2013. The time step in the available river flow data was 15 minutes, so the time step in the model was also set to 15 minutes.

Comparison and analysis

How well the model predicts adjustments between 2010 and 2013 is based on comparisons between modelled water edge elevation & cross section profiles at the end of the 2010-2013 model run and those measured during the fieldwork in 2013.

After the model run, the final new cross sections were exported as an input to the model. A discharge of 2.6 m^3/s was simulated to retrieve the water elevation as predicted by GRATE. Then the water elevation data were compared with the 2013 fieldwork data to validate the model.

However, after the model run it became clear that it was not possible to directly compare the output of the model (cross sections) with the fieldwork 2013 cross sections as a validation of the model. The equations underpinning the model do not adequately deal with bank erosion. This means that the points in the cross sections are fixed in the horizontal direction. According to the GRATE results, there is no horizontal adjustment at all. But, when looking at the validation data, the river also adjusted over its width, for example cross section 14 (Figure 11). This was solved to continue working with an average bed level change. By this, it was possible to compare single cross sections from the model run with gathered cross section information from the fieldwork data.

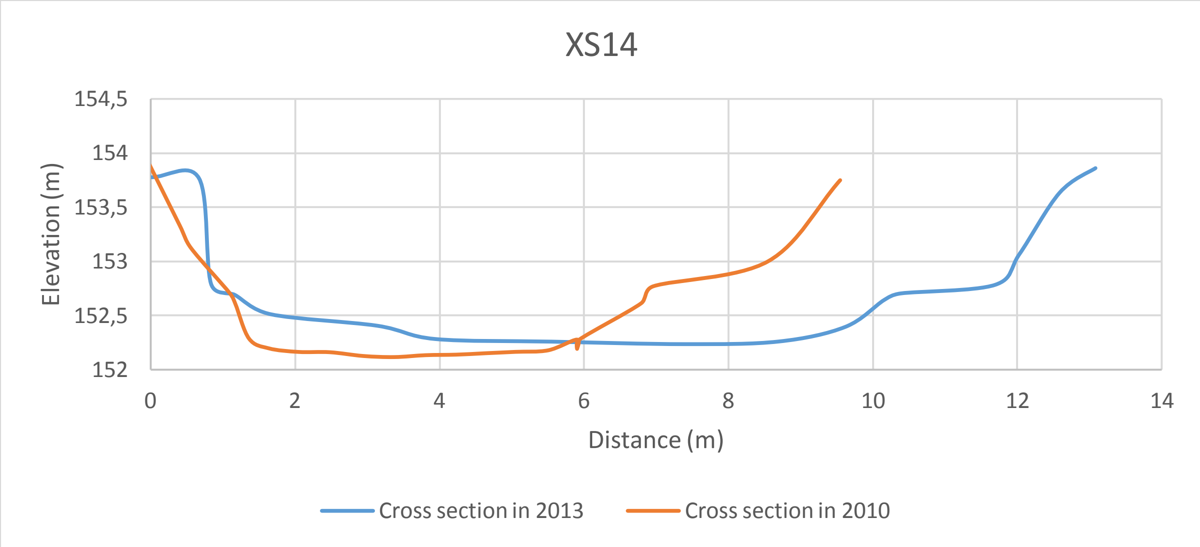

Figure 11 - Cross section 14 mainly adjusted in its width

The average bed level change was calculated by calculating the area in for example Figure 11 between the 2010 & 2013 survey bed elevations and the 2010 & 2013 model run bed elevation. The area divided by the width of the cross section gives you the average change in bed elevation between the 2010-2013 surveys and the 2010 survey & 2013 model run. These average changes are consistent with each other and can then be used to compare the model run with the 2013 survey data.

3 Results

The results are divided in five sections: the direct effects of the quake on the river, the predicted changes by GRATE, the morphological changes in real life, the performance of GRATE, and the predicted future changes.

3.1 Direct effects

Three different direct effects are identified: geological & hydrological effects and human intervention.

Geological

The diversion of the river was a result of so called 'oblique' east-side down slip on the north-western-striking of the fault, which means that the Greendale fault shifted both horizontally and vertically. The study area mostly suffered from vertical slip. In Figure 12 the lateral displacement of the fault is denoted by red arrows, the sides that went upside (U) and downside (D) are also shown(Quigley, et al., 2010). Also, according to Green & Cubrinovski (2010), liquefaction occurred in the paddocks near the river, distributed across several fields. Figure 1 shows an overview picture.

Figure 12 - Fault & flooding (Quigley, et al., 2010)

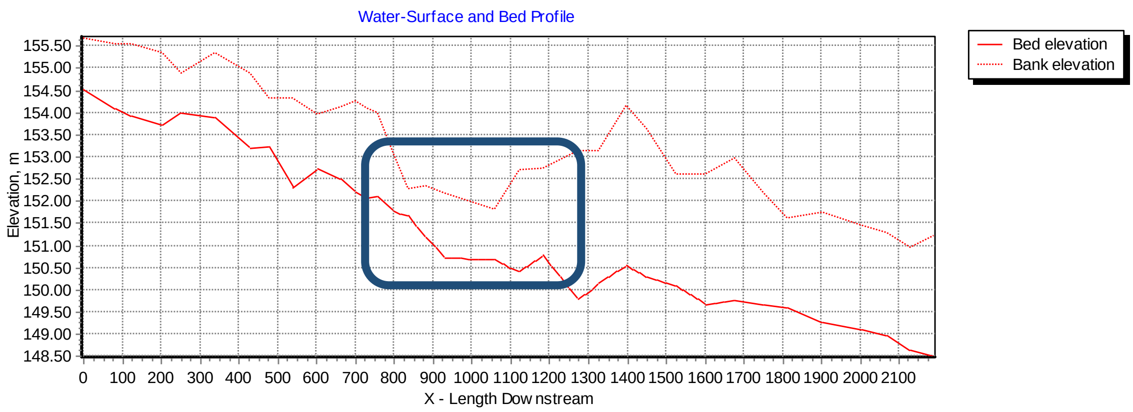

Figure 13 - Initial geological situation of river

In Figure 13, the situation of the bed level and top of bank elevation directly after the quake and the digging is visualised. The bank elevation is an approximate value of the highest point of both banks, but is not very accurate. The bank elevations are derived from the 2010 cross section profiles. Almost 300 meters of the river bed has dropped down, marked with a blue frame. The fault line cut the stream at around 800 meters and 1100 meters downstream from the start of the surveyed length. This can be seen in Figure 13, the bed and bank elevations drop is very noticeable between these locations.

The average drop of bed elevation is around 1.5 meters. The original slope of the river bed is 0.0028. This is an average as there are always natural variations in the channel. However, the section of the river immediately downstream of the fault (around river distance 800 meters, Figure 13) has a slope of 0.0065, which is very high. The elevation of the 'top of the banks' increased after the fault line, due to the human interventions. The cause of this increase is discussed in the 'human intervention' section below. This bed elevation profile is used as the start situation in GRATE.

Hydrological

Because half of the meandering bend dropped down, the water could not continue its course in the original channel. It spilled over the left bank, creating a large flood, see Figure 14. Also, water escaping from the river upstream of the study area flowed overland and re-joined the river within the study area between cross sections 16 and 17 from the northwest. This increased the magnitude of the flood, because more water was delivered to the river than it could handle. At the location of the meander, a lake of approximately 400 meters wide was formed.

Figure 14 - River flooding (meander is near the trees in the middle of the picture)

Also within the river channel some changes were visible. At the locations where the fault cut the river, small 'waterfalls' occurred. The geomorphic term for these in this situation are 'nickpoints'. The river bed slope was relatively very steep, resulting in flows that were supercritical. After the human intervention, the river returned to its original course. The 2010 survey (after the human intervention) was done during a discharge of 2.6 m^3/s. The water elevation for the surveyed length at this specific flow is shown in Figure 15. The slope of the water elevation shows a drop at 800 meters downstream. Propably, this is attributable to the change in river bed elevation/slope.

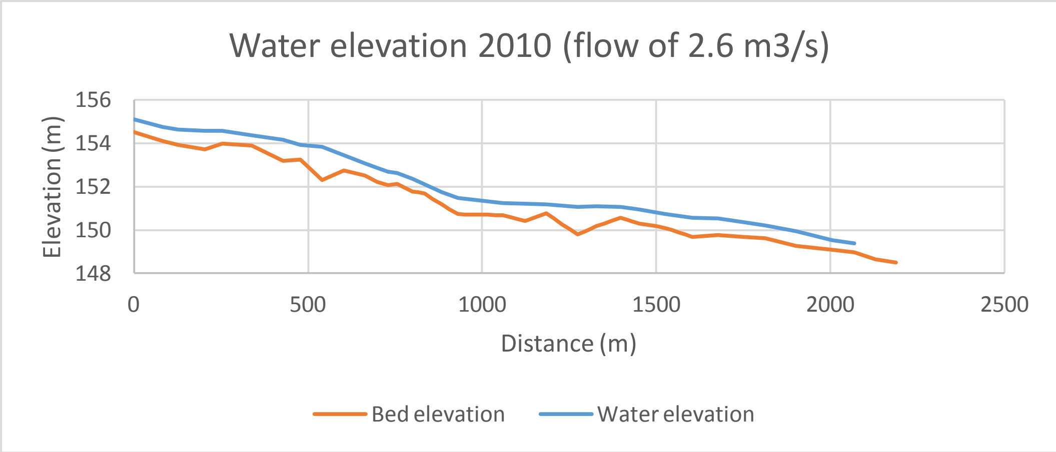

Figure 15 - Water elevation 2010, initial setup GRATE

Also, because of the drop in top of bank elevation in the bend, the surrounding land flooded quicker at lower discharges than before. The difference between the bank elevations within and outside the meandering bend are relatively large, see Figure 13.

Human intervention

Downstream from the meandering bend, a farmer living next to the river dug out the channel to allow the water in the original channel again. He used a digger to dig out the river bed and banks, depositing the excavated material on the sides of the river, raising the height of the banks. The width of the river was fixed, following the original channel. Compared with the original channel, the new banks are very steep, see Figure 16. The section of the river that was modified by the farmer starts at cross section 20 and ends at the end of the survey length, cross section 35. This section is about 800 meters long. The effect of the digging was that the flood levels in the paddocks quickly reduced to 5 cm(The New Zealand Herald, 2010). All the vegetation was removed from the river bed and banks, this resulted in a different roughness coefficient in these sections. See Figure 1 for the location of the dug out area.

Figure 16 - Channel upstream (left) and downstream (right) of fault & drop

Also, the capacity of the river was enlarged. This prevented flooding in combination with the steep high banks of the river channel (however not in the sections upstream of the manual digging). During the 2013 fieldwork it became clear that the farmer still manually adjusts the river. Unfortunately, there is no data available from these adjustments, so they cannot be quantified. Because of this, morphological changes surveyed in 2013 may incorporate both natural river adjustments (which should be simulated using GRATE) as well as man-made adjustments. It might seem that the results of the simulation are wrong in this situation. However, it is possible that the prediction of the model is correct in terms of the natural adjustment but that it is missing the human modifications. Fortunately, the farmer only dug recently at the very end of the surveyed length, between cross section 30 and 35. The areas around the fault line are untouched.

These results were used to create an initial situation in GRATE. With this data, a model run was done to predict the changes at the end of the period 2010-2013. These predictions are presented in the next section, starting with a calibration of the model.

3.2 Calibration of GRATE

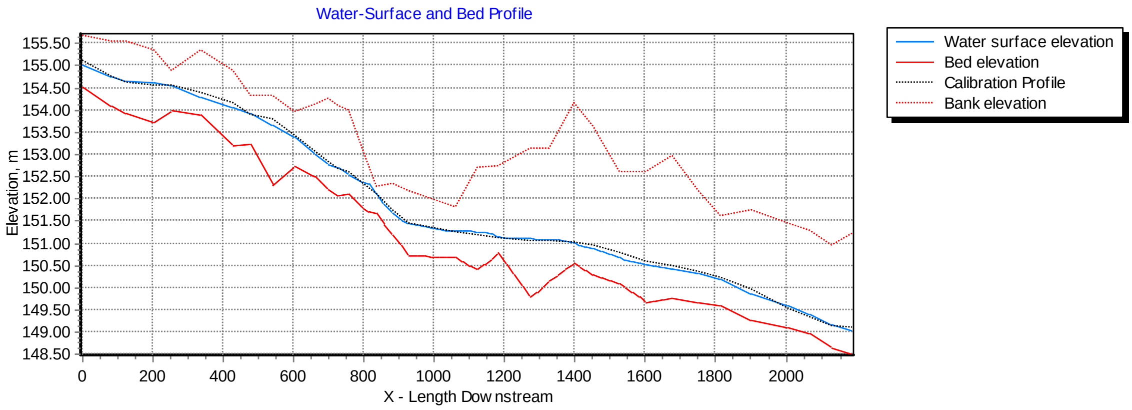

Figure 17 - Calibration profile 2010

Manning's n values vary in the range of 0.02-0.045 with an average value of 0.0303, resulting in a good fit, according to Figure 17. According to Hicks & Mason (1998), these are typical values for a natural stream with a gravelly river bed. The coefficient in the manually excavated channel is lower and before the fault line slightly higher than the average value. The Nash-Sutcliffe coefficient (NS-value) and the Relative Volume Error (RVE) were used as they are good indicators for hydrological model simulation and behaviour. The calibrated cross sections have a NS-value of 0.857 and a RVE value of -3.04%. NS-values between 0 and 1 are acceptable, indicating good model performance(Moriasi, et al., 2007); the values of the RVE should be between -5 % and +5%(Gumindoga, 2010).

Also, a morphological calibration is performed. The sediment inflow upstream is calibrated so that the model behaves properly. The cross sections are adjusted. Before, in case of a high discharge, the model behaved badly because the left and right boundary of the cross sections was infinite. GRATE cannot handle this very well. Therefore, there was a virtual dyke added to both ends of the cross sections. This made the model calculate the sediment transport in the river banks correctly.

3.3 Predicted morphological changes (GRATE)

The output of the model GRATE is presented in these sections. The results of the model run in terms of predicted bed elevation change are shown in Figure 18. A prediction for individual cross sections is presented in Appendix V.

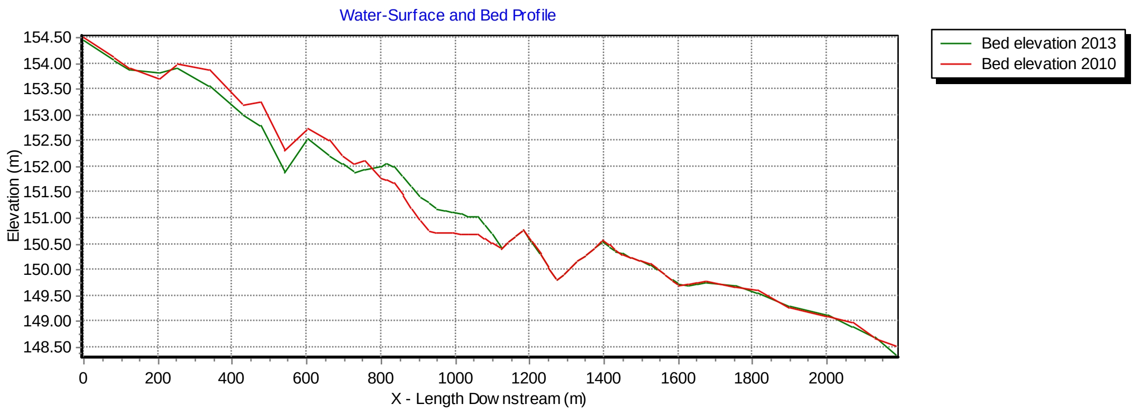

Figure 18 - River bed elevation change

The model predicts that there will be only changes around the fault line, from 200 meters to 1100 meters river distance. The sections consist of cross sections 4-19. The model predicts that the part of the channel that was manually adjusted will not change very much. The bed level upstream of the fault line will mainly degrade and the bed level between the fault line and the start of the newly excavated channel will aggrade. Note that these elevations represent the lowest points in the cross sections from the 2010 survey data. The slope of the river should be restored to normal levels according to the model.

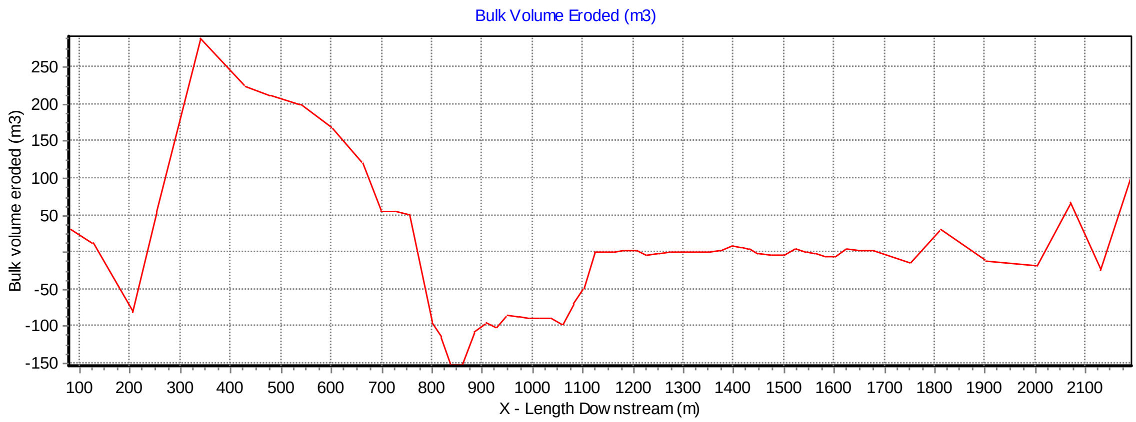

Figure 19 - Eroded volume (m3) for period 2010-2013

Although the sediment input from upstream is very low, there is a lot of sediment transport in the simulated sections, especially around the drop. Figure 19 shows the predicted eroded volume per distance downstream. From 200 to 800 meters downstream there is a lot of erosion. This material is carried by the river for only a short distance, because a lot of sediment deposits directly after the drop. Also, the manually dug out channel shows no sign of erosion and deposition, except for the end of the surveyed reach. There is a bridge at this location, forming a bottleneck. If the predicted erosion at this location eventuates then the river could erode the foundations of the bridge.

The water elevation at a discharge of 2.6 m^3/s is visible in Figure 20. Note that at some sections, the elevation is a bit rough, for example 800 meters. This is due to the quasi-steady flow simulation. A fully dynamic flow simulation would have shown a smooth water elevation. For the calculation of sediment transport however, this is not a problem.

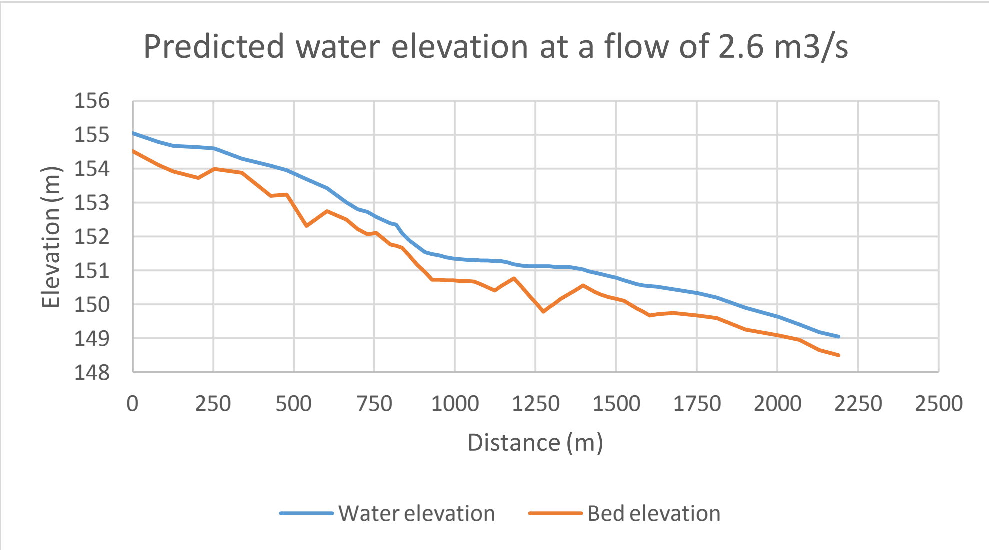

Figure 20 - Water elevation 2013 as predicted by GRATE

3.4 Observed morphological changes (fieldwork)

The morphological changes surveyed in 2013 are then compared with the simulated and predicted changes.

Comparison of surveyed water elevation 2010-2013 and model run

A direct comparison between the measured water elevations of 2010 and 2013 can be made due to fieldwork surveying. The surveying was done during the same discharge in both years. In Figure 21, the lines represent these elevations. The water level has slightly risen in 2013 in both the measured and model predicted results. Also, it looks like the water level drop ('nickpoints) at distance 800 meters has faded out, since the line (slope) of 2013 is not as steep as the 2010 one. However, the river slope is still locally steepened, which will likely result in further adjustments, as discussed in section 3.6. Also remarkable is that the adjustments only occur over a 500 meter reach around the drop location. Beyond this 500 meter reach, upstream and downstream of the drop there are no significant changes visible, except for last sections of the downstream part. But, this predicted deviation at the downstream end of the reach is due to a model error rather than real adjustments in the field. Namely, the water elevations for the sections 1500-2000 meter downstream of the 2010 and 2013 surveys show that the adjustments are not as big as predicted by the model. The cause of these deviation is, as previously explained, the man-made adjustments.

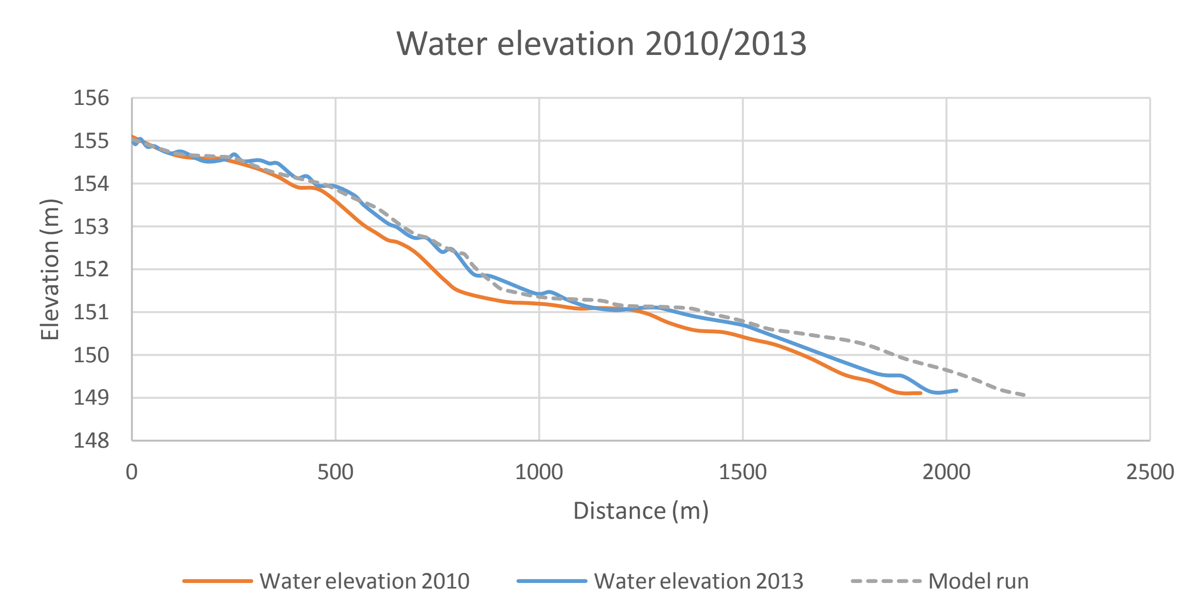

Figure 21 - Water levels

The model run results are also visible in Figure 21 (grey line). A first sight, the model seems to predict quite well how the water elevation changes. Linked to this is a good simulation of the change of river bed.

Figure 18 only shows the lowest point of every cross section. Using only these points gives no information about changes in individual cross sections. So, a comparison between individual cross sections was made. This comparison includes a validation check, Table 2. The average bed elevation change in individual cross sections was calculated for both the model output and the 2013 survey data. To be consistent, the average change has to be either positive or negative for both model output and survey data. If this is the case, the GRATE simulation is predicting erosion and deposition in an accurate way. Another assessment of results was done with the net change in elevation. The average change in elevation has to be in the same order of magnitude for both model output and survey data. When the model meets these two conditions, the model precision is accurate. All surveyed cross sections can be found in Appendix V. The graphs in the appendix comprise the 2010 survey data, the prediction of the model for 2013 and the 2013 survey data.

Table 2 Assessment results

Cross section	Comparison between	Average change in elevation in cross section (m), positive numbers indicate deposition, negative numbers indicate erosion	Over-/underestimation of average change in elevation (m)	Direction of change correct?
12	Model simulation	0.159818	0.065295	Yes
	2013 survey	0.094523		
13	Model simulation	0.159958	-0.021736	Yes
	2013 survey	0.181695		
14	Model simulation	1.11835	0.674046	Yes
	2013 survey	0.444304		
15	Model simulation	-0.19748	0.12591	Yes
	2013 survey	-0.07157		
16	Model simulation	-0.45936	-0.575728	No
	2013 survey	0.116368		
17	Model simulation	-0.343	0.33643	Yes
	2013 survey	-0.00657		
18	Model simulation	-0.4667	0.4631	Yes
	2013 survey	-0.0036		
19	Model simulation	-0.34174	0.51575	Yes
	2013 survey	-0.85749		
20	Model simulation	0.044603	0.13505	Yes
	2013 survey	0.179653		
Average over/underestimation of change in elevation in study area(m):			0.190902	

It turns out that almost all cross sections are simulated in a consistent way, Although the degree of average change in elevation is not perfectly simulated, the model predicts accurately what the river bed is doing, except for cross section 16; either degrading (erosion) or aggrading (sediment deposition). However, the overestimation of change in cross section 16 is not the maximum overestimation. For example, the overestimation in cross section 14 is much larger. The explanation for the large deviation between model run and the 2013 survey is that the river also changed in its width. A larger change of width is related to a lower change in elevation. As stated before, the model only simulates vertical changes (erosion/deposition).

3.5 Usefulness of GRATE

The appropriateness of using GRATE in this project is checked in two ways: calibration and validation. The calibration is already done. The morphology validation has already been done, see Table 2. The water elevation validation is done in this chapter.

To validate the results of the model, the water elevations were measured during the two surveys. The water elevation obtained after the model run is subsequently compared with the 2013 water elevation data. There were obstacles in the water in 2013, so the last 165 meter was not measured. That is why the blue and grey lines are not of the same length in Figure 22.

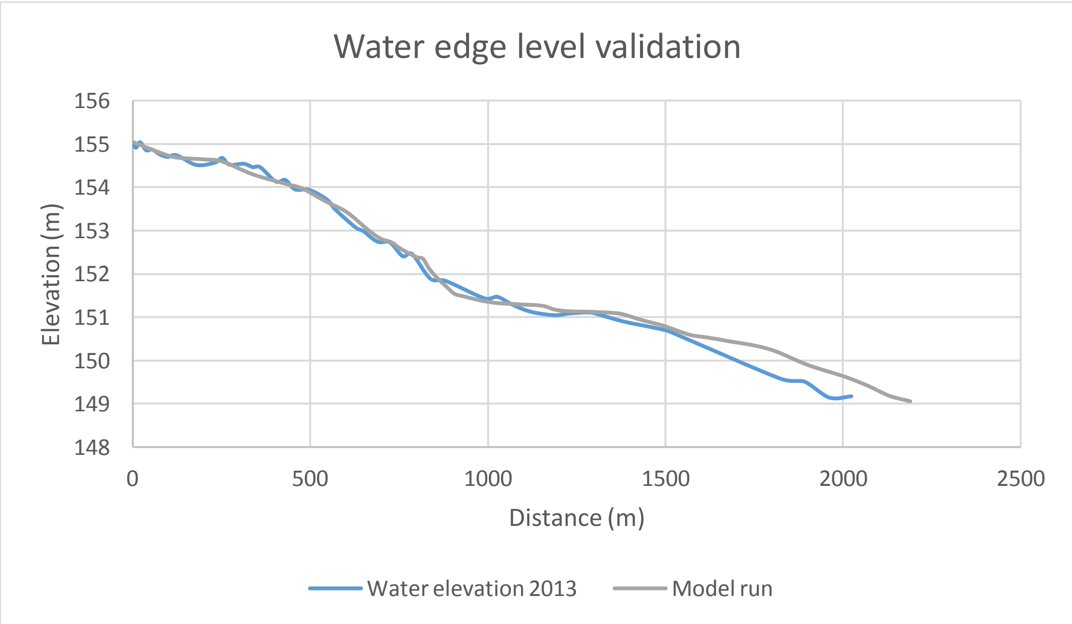

Figure 22 - Validation of water levels

Generally, the two water elevations fit closely together. Except for the last 500 meters of surveyed length, the slope and value of the simulated water elevation fits the observed slope and values. However, there is a large deviation at the end of the surveyed length. This can be explained; the river has recently been manually deepened here to protect a bridge at the end of the study area. The farmer dug out the channel locally (~1200-2000 meters downstream from the start of the study area), as stated before. Also, due to the recent digging, there was no vegetation on the river bed and banks. The roughness coefficient of the river in these sections is lower than used as input for the model. Therefore, the model overestimates the water levels.

Some statistics were calculated to compare the two elevations, Table 3. This includes the large deviations at the end of the surveyed length.

Table 3 - Validation full survey length

0 – 2004 meters	Average elevation of study area (m)	Average difference in elevation of study area (m)
2013 survey	151.9859	
Model run	152.1063	
Difference 2013 survey & Model run		-0.1203

So there is an average deviation of 0.1203 meters between the two elevations. This is not bad and does reflect the calibration. However, the main focus of the project is the area between 500-1500 meters downstream. So the last 500 meters can be skipped for validation. In that case, the statistics are (Table 4):

Table 4 - Validation survey length excluding the last 500 meters

0 -1500 meters	Average elevation of study area (m)	Average difference in elevation of study area (m)
2013 survey	152.6958	
Model run	152.7263	
Difference 2013 survey & Model run		0.111552

The precision did not improve much when omitting the last part of the survey. It seems that the model simulates the water levels very well. The last section has a large deviation, but does not throw a spanner in the works, as the average difference between the elevations increase from 0.11 to 0.12 meters. Because the main focus of the assignment is not directed on the last section, that one will be emitted from validation. The average difference of the water elevation is then 0.11 meter, which is considered to be acceptable model behaviour.

3.6 Future of the Hororata River

The adjustment of the Hororata River until April 2013 is now known. What is going to happen in the future? Another model run was done, with the adjusted cross sections (April 2013) as an input. Using the same options, assumptions and time steps as before, a simulation was run for the period April 2013 – November 2015. The results are presented in Figure 23.

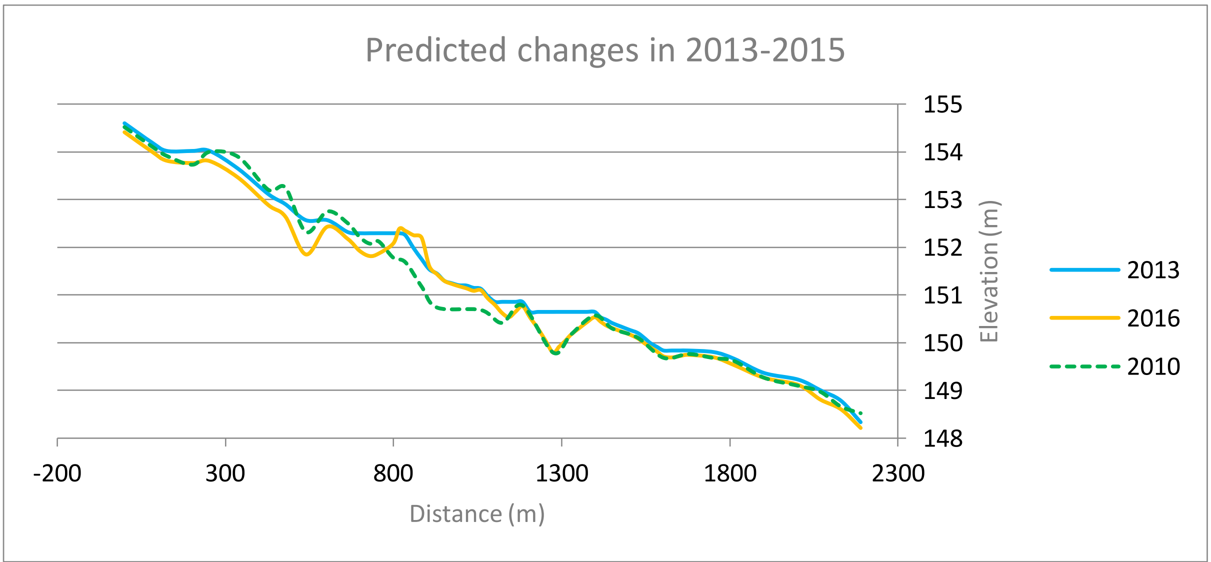

Figure 23 - Future changes

Although there is a lot of distortion in the simulation, the river slope continues to flatten out. The 'restoration' of the old river channel will continue, according to GRATE. Notable is that the channel dug out by the farmer (1200-1600 m downstream) still does not adjust very much, just as in the period 2010-2013. Because the assumptions in this model run are the same as used in the 2010-2013 model run, there is almost no change in bed elevation in this section.

It is expected that the farmer will continue to adjust the river. At some places across the bend, the banks are too low. The possibility of floods is very high during a year. To protect his land, the farmer need to raise the banks. The elevation of the banks can be found in Figure 13, they are very low in the meandering bend in comparison with the rest of the study area.

4 Discussion & recommendations

The model assumes that Manning's n is constant throughout different discharges. However, this is not the case. The roughness of a river typically changes with increasing discharges, depending on vegetation and other form roughness factors. GRATE cannot calculate different roughness coefficients during a model run. It can be an idea to add this in a new version of GRATE.

Due to wrong model behaviour, a morphological calibration was performed. This included adjustments to the individual cross sections in order to let the model calculate the sediment transport in the river banks correctly. Also, the sediment input rate of the model was calibrated.

Another point of discussion is the usefulness of the one dimensional model. These models are relatively simple to understand and can be used to quickly simulate long periods of bed level evolution. However, they lack the capability to predict the detail of changes within across section. For example, the equations that underpin the model don't adequately deal with bank erosion. The vertical change of the river bed is constantly overestimated in the simulation, while fieldwork proves that there has been a lot horizontal adjustments as well.

The 2013 fieldwork was done in May and June 2013. The simulation only ran until April 2013. The river probably slightly changed in the period between April and May, this may explain small deviations between the simulation output and the 2013 survey data. Also, the bedload feed rate at the upstream part of the 2013 survey is possibly not complete. The captured data only contained information about the grain size fractions between 8 and 128 mm. It is possible that there is finer sediment material present. Sediment calibration showed that there might be finer material. As a result, the bedload feed rate might be underestimated. In order to increase the quality of the simulation, more information about the size fractions should be collected. Furthermore, the 2010 data set was not complete. For example, there was no bed material data available. To solve this, bed material was gathered in 2013 and the assumption was made that the 2013 dataset represents the 2010 dataset. However, the bed (and its material) might have changed in the period 2010-2013. This makes the reliability of the grain size distribution data uncertain for model use, as the initial setup needs information about the situation in 2010.

There is almost no sediment input from upstream according to the model. The amount of sediment input is calibrated and based on sediment data collected in the field but that collection may not be representative of sediment supply coming into the model in reality. When looking at Figure 19, there is a surplus of sediment in the study area. There are a few possible explanations for this: the sediment comes from inside the surveyed river length or the input bedload feed rate is not correct. The river banks eroded locally, bringing sediment into the river upstream of the fault line. But, it is also possible that the sediment input rate at the most upstream point of the study area is underestimated. In reality there may be more sediment coming in but it may be finer and not measured. This material is not depositing in the study area, creating a surplus of sediment. Another explanation is that the assumption was made that the grain size distributions are not equal in the study area. There might be spatial deviations along the river bed.

The amount of erosion before the drop seems much higher than the deposition after the drop. The large erosion can be explained by the steep slope and drop over here, creating higher water velocities and therefore more erosion. The deposition can be caused by the relatively large channel after the fault line. The river loses energy in this section, inducing deposition. Another explanation is that the porosity of the deposited layer is lower than the porosity of the eroded layer, as a result, the quantity of deposition seems lower than the amount of erosion.

The part of the river that was dug out by the farmer does not change very much. Deposition and erosion are very low. A possible explanation is that the energy of the river is already broken before this section. The meander bend before the humanly adjusted channel is very sensitive to floods, and erodes and deposits a lot of sediment during a flood. Also, the banks themselves are breaking the rivers energy due to some kind of protection. Possible factors are thick vegetation or that the banks are made of other materials that are much better resistant against erosion.

There are a few river sections that have been heavily eroded in their width. The farmer has strengthened the banks with large rocks at these places, to prevent further bank erosion. But, other unprotected sections (like river bed and other banks) may fall victim to the river and will erode. So it might be that the degree of erosion and deposition is not the same as the model predicts. The speed at which the slope of the river recovers consequently can change. The river can adjust both its bed and banks. It is unsure if the farmer will continue strengthen unprotected sections. If so, bank protection may encourage bed erosion if there is excess energy in the river that need to be dissipated. If not, the river will probably continue to erode his banks and deposit sediment right after the drop in order to restore the slope of the river.

The area around the river is geologically very active. In the direct neighbourhood of the river channel are rifts and other signs of fault rupture visible. This indicates that there are several other faults in the region, and some of them hidden and unknown to researchers and specialists. It is not excluded that an event like the big 2010 earthquake can happen again in the near future, disrupting the Hororata River again. The model can be used to understand the problems rising in that case. Also, bottlenecks and other issues with adjusted river sections can be resolved using the model, because it is possible to simulate the effects of these problems. However, the model should be calibrated and validated again to adapt to the new changes.

5 Conclusion

There are 4 important aspects that need understanding before a statement can be made about how the Hororata River has adjusted in response to the effects from the Canterbury earthquakes: direct effects, changes according to model simulation, changes in real life and the usefulness of the model GRATE in this specific situation.

What were the direct effects of the 2010 earthquake with respect to the Hororata River?

Around 300 meters of river bed has dropped 1.5 meters down due to an oblique down slip of the Greendale fault. This resulted locally in an increase of river bed slope of 2.3 times the average slope. The river could not access the main channel after the meander anymore, causing flooding on adjacent paddocks. Also, a small lake formed at the location of the meander bend. Because of the drop, the river banks in the bend became more sensitive to flooding. A farmer excavated the downstream channel, in order to restore the original stream. He created relatively high and steep banks, in order to keep the river where it flows.

What morphological changes are predicted by the model GRATE for the period 2010-2013, what is the morphology of the river in 2013 and which adjustments did take place?

According to the simulation of GRATE, only adjustments occur around the meandering bend. Validation data proved the correctness of the simulation and indeed, only changes were visible near the meandering bend. The river bed slope around the fault line were relatively steep after the earthquake. The drop of land and river bed were the main cause. After three years, both the model run and the 2013 survey data showed that the slopes of the reach around the fault line have evened. The river is restoring the slope to the levels before the earthquake. The model indicates that there is almost no sediment input from upstream the study area. However, there are several indications that the sediment input rate is higher than assumed. In the humanly enlarged channel are virtually no adjustments. This can be explained because the energy of the river is probably lower in these sections than in the rest of the study area.

The GRATE simulation is predicting erosion and deposition in an accurate way. The simulation calculates the vertical adjustments of the river with an average deviation of 0.20 meter. There are no horizontal changes possible in GRATE (bank erosion processes are not currently well represented in this model). However, GRATE may be predicting the degree of adjustments adequately, but not the nature of the adjustment. Generally, GRATE can predict the adjustment of the river very well.

How well does the GRATE model predict the measured water levels and changes between 2010 and 2013?

The model simulation is calibrated for a river flow of 2.6 m^3/s. The calibrated parameter is the roughness coefficient of the cross sections, Manning's n. The value of this coefficient ranges between 0.02-0.045. These values are typical when compared with similar river beds, making the calibration plausible. The model behaviour indicators, NS and Relative Volume Error (RVE), are respectively 0.857 and -3.04%. Thresholds are between 0 and 1 for NS and between -5% and 5% for RVE. This means that the calibration is of sufficient quality.

The validation due to 2013 fieldwork material proved the precision of the model. Because the farmer recently did some digging in the last section of the channel, this part is not correctly simulated by GRATE. The average difference in water surface elevation between the simulation and survey data is in that case 0.12 meter, which is good. If the deviating sections are omitted, the average difference becomes 0.11 meter. The effect of the deviations on the precision of the model is not large.

Future

GRATE predicts ongoing river adjustments for the period 2013-2016. The slope of the river will eventually be restored to levels before the earthquake. However, the speed of these adjustments and restoration depends on the farmer. Bank protection may encourage bed erosion if there is excess energy in the river that need to be dissipated. This will lead to a quicker restore of slope. If not, the river will probably continue to erode his banks and deposit sediment right after the drop in order to restore the slope of the river.

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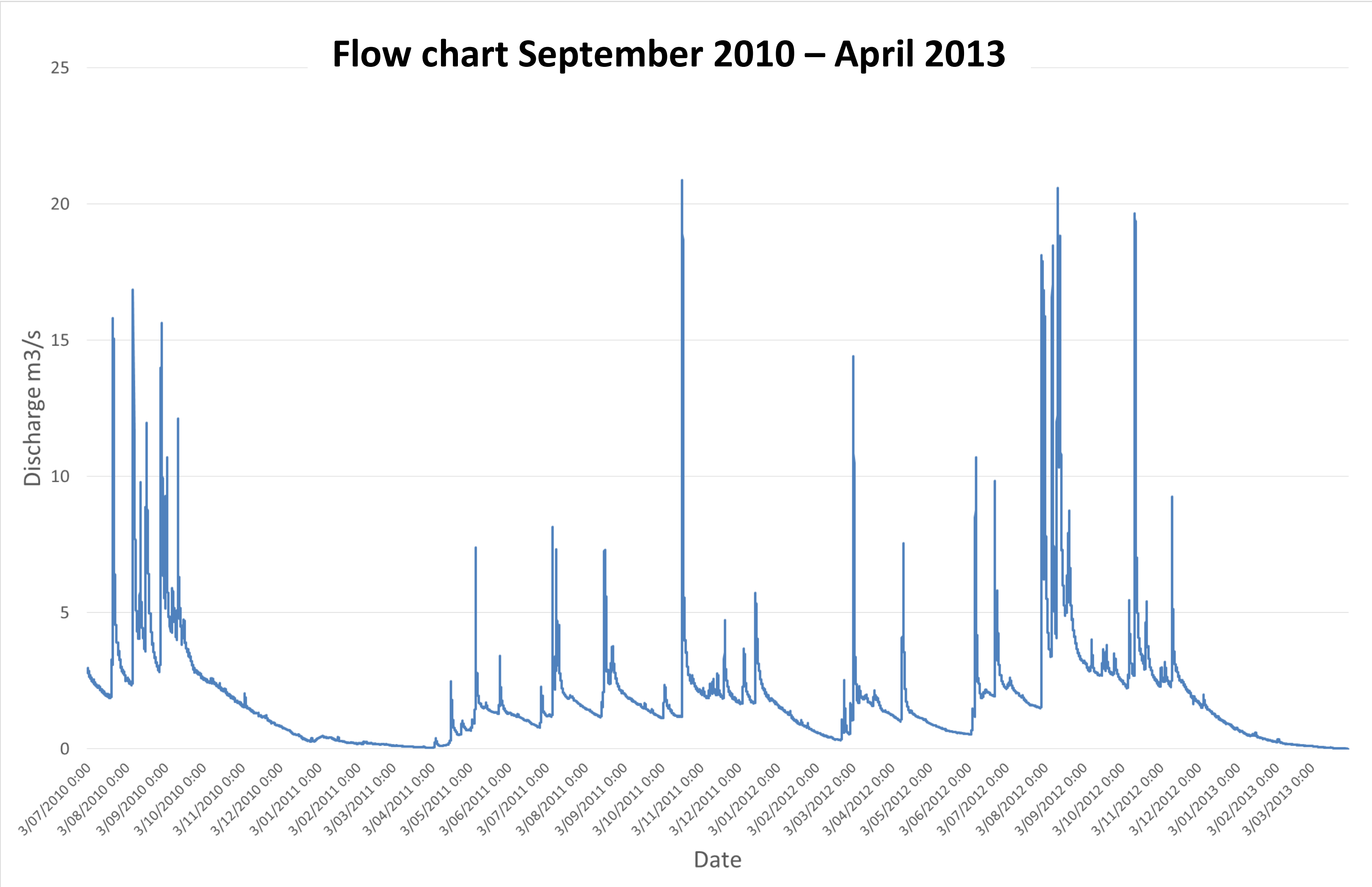
Appendices

I. Flow time series



II. Wolman & bulk samples

Wolman	XS1	XS8	XS12	XS16	XS19	XS24	XS34
Distance downstream (m)	0	478.6893	698.9879	835.2927	1059.491	1398.278	2130.491
Grain size (mm)							
512	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
380	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
256	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
181	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
128	100.00%	100.00%	100.00%	98.08%	100.00%	100.00%	100.00%
90	98.26%	100.00%	93.33%	91.35%	99.15%	97.03%	95.41%
64	87.83%	99.07%	68.57%	83.65%	95.73%	80.20%	75.23%
45	66.09%	90.74%	30.48%	71.15%	91.45%	50.50%	50.46%
32	50.43%	75.00%	13.33%	53.85%	75.21%	25.74%	32.11%
23	27.83%	48.15%	2.86%	36.54%	55.56%	7.92%	9.17%
16	12.17%	16.67%	1.90%	21.15%	27.35%	2.97%	0.92%
11	1.74%	7.41%	0.00%	6.73%	6.84%	0.00%	0.00%
8	0.00%	0.00%	0.00%	2.88%	0.85%	0.00%	0.00%
6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Bulk	XS16	XS24				XS16	XS24
Grain size (mm)					Grain size (mm)		
256.0	100.00%	100.00%			**0.250**	1.51%	0.90%
181.0	100.00%	100.00%			**0.177**	1.51%	0.90%
128.0	100.00%	100.00%			**0.125**	0.82%	0.46%
90.5	98.77%	99.32%			**0.088**	0.82%	0.46%
64.0	93.30%	92.85%			**0.062**	0.44%	0.22%
45.3	83.32%	83.19%					
32.0	67.94%	70.77%					
22.6	52.28%	57.75%					
16.0	38.92%	49.45%					
11.3	29.81%	39.08%					
8.0	22.80%	29.90%					
5.7	18.95%	22.39%					
4.0	15.77%	16.41%					
2.8	13.24%	12.45%					
2.000	11.06%	9.18%					
1.414	9.10%	6.78%					
1.000	7.25%	4.87%					
0.707	7.25%	4.87%					
0.500	3.71%	2.25%					
0.354	3.71%	2.25%					

III. Flow vs. sediment inflow

Flow (m3/s)	Qs (kg/s)
0	0.00000
1	0.04113
2	0.13829
3	0.34704
4	0.55243
5	0.78191
6	1.03046
7	1.30286
8	1.59697
9	1.90793
10	2.22918
11	2.55296
12	2.92075
13	3.29232
14	3.66677
15	4.04413
16	4.42366
17	4.80403
18	5.18785
19	5.57260
20	5.91675
21	6.26392

IV. GRATE input file

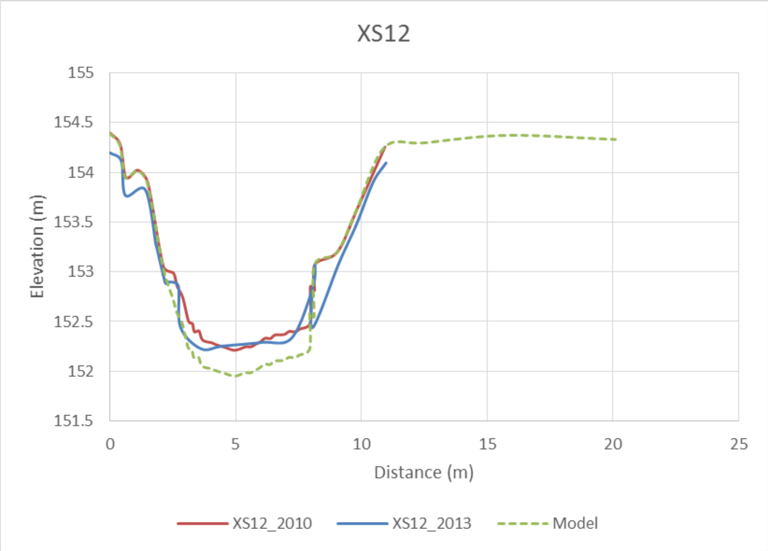
```
! ========================================================================
! GRATE - Input for Horizons Rivers Study 2013
! ========================================================================
 RUNID = Hororata_RiverOctober2010
 MODELTYPE = 4
! ========================================================================
! Simulation Time
! ========================================================================
 TS = 20100703 001500            ! Start time in ISO format (yyyymmdd hhmmss)
TE = 20130401 004500            ! End time in ISO format (yyyymmdd hhmmss)
 NO_CYCLES = 1          ! Number of cycles of time interval (TS - TE) to process     (default = 1)
MAX_DT_QS = 60     ! Maximum time increment in secs  (Quasi-steady run)
 MAX_DT_FD = 1     ! Maximum time increment in secs (Fully Dynamic run)
 MAX_DX = 999 ! Maximum spatial increment in metres
 CDT = 0.025                    ! Measure of permissible BL change over DT (m)
MAX_DQ_OVER_DT = 0.1    ! Maximum increase in q over a time increment
! ========================================================================
! Parameters
! ========================================================================
 LAYER = 10          ! Layer thickness (m) - Storage Layer
 LA = 0.1            ! Layer thickness (m) - Active Layer
 NBS = 1             ! No of storage layers excluding the active layer and including the infinitely thick bottom
layer.
 PORO = 0.4          ! Porosity of the deposit
 ALPHA_S = 100        ! Non-equilibrium adaptation coefficient (Armanini & De Silvio, 1988)
 NEQAL = 20          ! Bedload Non-equilibrium adaptation length option
 DK = 1.5            ! Roughness height/static d90 (for determining equivalent sand grain roughness)
 QTHRES = 0        ! Threshold flow below which no ST occurs and a longer time-step (20x) is applied
REFGSZ =  1.690046E-02        ! Reference grain-size for dimensionless shear stress display (m)
REFNODE = 4       ! Computation node at which outputs are calculated and displayed on screen (default
= last node)
! ========================================================================
! Discretisation Parameters
! ========================================================================
THETA = 0.6          ! spatial weighting coefficient in HD Scheme (fully dynamic only - Default=0.6)
THETA_S = 0.8      ! spatial weighting coefficient in ST Scheme (non-equilibrium only - Default = 0.8)
PSI_S = 1.0          ! temporal weighting coefficient in ST Scheme (non-equilibrium only - Default = 1.0)
! ========================================================================
! Bed Layer Setup
! ========================================================================
 BLOPT = 2
! ========================================================================
! Active Layer Setup
! ========================================================================
ALOPT = 1
! ========================================================================
! CROSS - SECTIONS - Model Type 2 - Natural River
! ========================================================================
 XSECTFILE = Hororata_RiverOctober2010XS_Int25m.dat
! ========================================================================
! Inflow Boundary Conditions
! ========================================================================
```

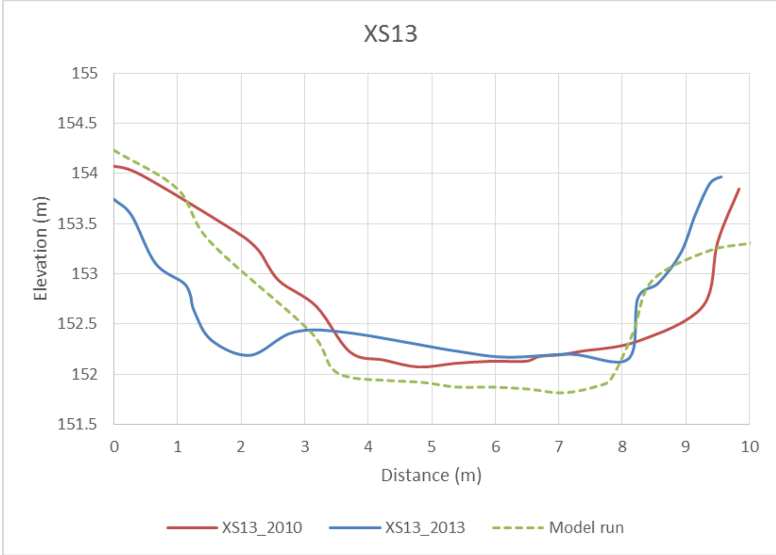
```
 NQBC = 1       ! No of Flow Boundary conditions (one at X0 is essential)
0.00  TS  Hororata_RiverOctober2010Flow_TS.dat
! ============================================================================
! Downstream Water Level Boundary Condition (applied at Maximum Chainage)
! ============================================================================
 N  2.74813E-03  149.104

! ============================================================================
! Sediment Inflow Boundary Conditions
! ============================================================================
 NSBC = 1       ! No of Sediment Boundary conditions (one at X0 is essential)
0.00  TS 2 1 Bedload_feedratenew.dat
! ---------------------------------------------------------------------------
! Sediment Extraction Boundary Conditions  (applicable for nlayer=2 models only)
! ---------------------------------------------------------------------------
 NXBC = 0       ! No of Sediment Extraction Boundary conditions
!   <xc> <code> <Qs> <ps> (for CODE = 'C')
! ---------------------------------------------------------------------------
! Sediment Ripping Event Boundary Conditions  (applicable for nlayer=2 models only)
! ---------------------------------------------------------------------------
 NRBC = 0       ! No of Ripping Event Boundary conditions
!   <xc>  <fname>   (file of time, ripping depth pairs)
! ============================================================================
! Grain-Size Profiles
! ============================================================================
 NGRP = 2    ! no of Grain size profiles
 NGSZ = 14 !no of grainSizeintervals between 0.063 mm and 1024 mm
 NLITH = 1   ! no of lithology groups
! ABRASION_COEFF
 0
! SEDIMENT_DENSITY
  2.65
!               1       2        ...      ngrp
! GRAIN SIZE (MM)  % FINER    % FINER    % FINER    % FINER ! VALUES
0.063            0       0
2               0       10.12
2.8              0       12.85
4               0       16.09
5.6              0       20.67
8               0.53     26.35
11.3             3.24     34.44
16              11.88    44.18
22.6             26.86    55.01
32              46.53    69.35
45              64.41    83.26
64              84.33    93.07
90              96.36    99.05
128              99.73    100.00
181             100      100.00
! ---------------------------------------------------------------------------
! Specifiy lithology fractions for each grain size and group (percentage, not cumulative)
!                     1         2        ...      ngrp
!      LITHOLOGY GROUP     % PCT    % PCT      % PCT      % PCT
 1  100  100
```

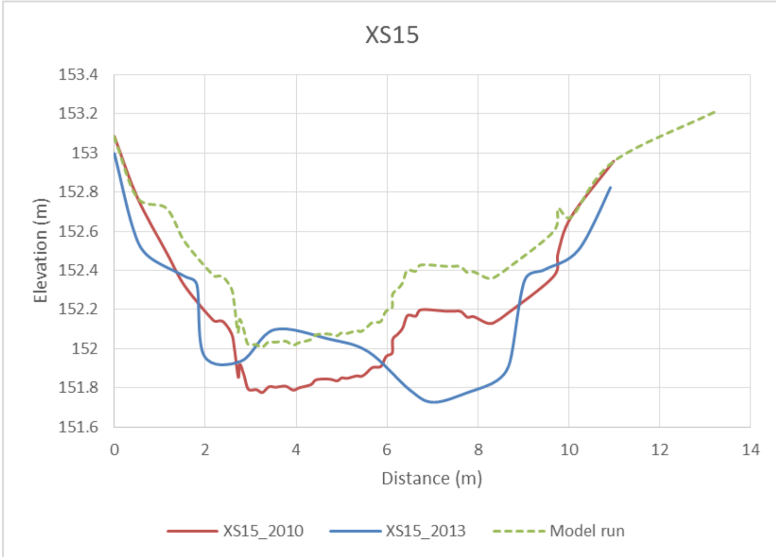
```
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
 1  100  100
! ========================================================================
! Print Options
! ========================================================================
  NPRTF = 720  ! print output every NPRTF*DT secs    (default = 300)
  OUTXSPARMS = 1  ! Flag to enable output of cross-section information (outxsparms:
0=Disable;1=Enable)
  OUTXS = 4   !  cross-section to output information on - this may  need to be the offset??
! ========================================================================
! Display Options
! ========================================================================
  SedAccum = 1             ! Units of sediment accumulator display (0=kt, 1=kg)
  ProfYAxisLimitsAuto = 1        ! Automatically set limits to Y axis in Profile plot (0/1 = No/Yes,
Default=Yes)
  ProfYmax = 100        ! Manual override for ymax (only used if ProfYLimitsAuto=0)
  ProfYmin = 0       ! Manual override for ymin (only used if ProfYLimitsAuto=0)
  ProfYint = 10        ! Manual override for y-interval (only used if ProfYLimitsAuto=0)
! ========================================================================
! Hydraulic calibration data: bankful level, water surface profiles
! ========================================================================
NCALIB = 2      ! Number of profiles
NCALPTS = 35  ! Number of points in each profile
0 155.1145  155.676  ! and so on for additional profiles
81.82978 154.7525  155.535  ! and so on for additional profiles
125.7311 154.632  155.555  ! and so on for additional profiles
203.3402 154.5625  155.342  ! and so on for additional profiles
252.8442 154.5635  154.875  ! and so on for additional profiles
338.3518 154.3725  155.331  ! and so on for additional profiles
428.0043 154.142  154.895  ! and so on for additional profiles
478.6892 153.909  154.312  ! and so on for additional profiles
539.5873 153.7965  154.317  ! and so on for additional profiles
603.4236 153.421  153.972  ! and so on for additional profiles
663.7355 153.0735  154.137  ! and so on for additional profiles
698.9879 152.8525  154.255  ! and so on for additional profiles
729.1354 152.676  154.084  ! and so on for additional profiles
755.9885 152.6085  153.982  ! and so on for additional profiles
799.1351 152.337  153.084  ! and so on for additional profiles
835.2927 152.0935  152.286  ! and so on for additional profiles
883.5662 151.763  152.344  ! and so on for additional profiles
929.6725 151.466  152.173  ! and so on for additional profiles
1059.491 151.2415  151.807  ! and so on for additional profiles
1123.15 151.181  152.697  ! and so on for additional profiles
```

```
1183.683 151.1305  152.723  ! and so on for additional profiles
1274.751 151.067  153.118  ! and so on for additional profiles
1327.751 151.0605  153.135  ! and so on for additional profiles
1398.278 151.034  154.171  ! and so on for additional profiles
1450.712 150.965  153.638  ! and so on for additional profiles
1525.529 150.7735  152.614  ! and so on for additional profiles
1603.304 150.582  152.618  ! and so on for additional profiles
1676.76 150.488  152.978  ! and so on for additional profiles
1753.625 150.374  152.173  ! and so on for additional profiles
1813.103 150.227  151.604  ! and so on for additional profiles
1901.621 149.96  151.754  ! and so on for additional profiles
2004.125 149.533  151.442  ! and so on for additional profiles
2069.737 149.333  151.298  ! and so on for additional profiles
2130.491 149.122  150.968  ! and so on for additional profiles
2189.264 149.104  151.214  ! and so on for additional profiles
```

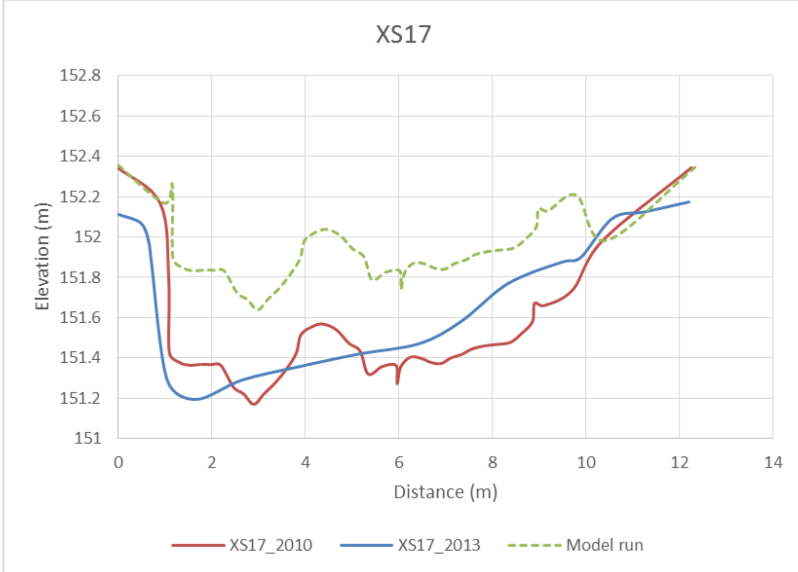
V. Surveyed cross sections








XS16
Elevation (m)
153
152.8
152.6
152.4
152.2
152
151.8
151.6
151.4
0
2
4
6
8
10
12
14
16
18
20
Distance (m)
XS16_2010
XS16_2013
Model run


XS17
Elevation (m)
152.8
152.6
152.4
152.2
152
151.8
151.6
151.4
151.2
151
0
2
4
6
8
10
12
14
Distance (m)
XS17_2010
XS17_2013
Model run


XS18
Elevation (m)
153.5
153
152.5
152
151.5
151
150.5
0
2
4
6
8
10
12
Distance (m)
XS18_2010
XS18_2013
Model run


XS19
Elevation (m)
152
151.8
151.6
151.4
151.2
151
150.8
150.6
150.4
0
2
4
6
8
10
12
14
16
Distance (m)
Xs19_2010
XS19_2013
Model run


XS20
156
155
154
153
152
151
150
149
Elevation (m)
0
2
4
6
8
10
12
14
16
18
Distance (m)
XS20_2010
XS20_2013
Model run