Modelling gravel transport, extraction and bed level change in the Ngaruroro River

Prepared for Hawkes Bay Regional Council

October 2012

Authors/Contributors:
Richard Measures

For any information regarding this report please contact:

Richard Measures
River Modeller
Sediment Processes
+64-3-343 8066
richard.measures@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
10 Kyle Street
Riccarton
Christchurch 8011
PO Box 8602, Riccarton
Christchurch 8440
New Zealand

Phone +64-3-348 8987
Fax +64-3-348 5548

NIWA Client Report No:	CHC2012-121
Report date:	October 2012
NIWA Project:	HBR12503

Contents

Tables

Figures

Reviewed by	Approved for release by
D M Hicks	
Murray Hicks	Jo Hoyle

Executive summary

A calibrated one-dimensional morphological model of the Ngaruroro River was constructed to simulate gravel transport and bed level change. The modelling had two main aims:

- Inform better understanding of the gravel transport processes on the river and investigate the impact of different drivers including gravel extraction, beach raking, changes in supply and climate change.
- Pilot the application of calibrated morphological models for informing gravel management in the Hawkes Bay Region. The process developed for modelling the Ngaruroro River should be applicable to other rivers in the region including the Tukituki River which is significantly more complex.

Surveyed cross-section data and sampled grain size data were used to construct the model which was then hydraulically calibrated against observed levels for two flood events. After hydraulic calibration, the model was run for the period 1977-2012, using flow and tide data for that period and incorporating the gravel extraction and beach raking which occurred during those years. The sediment transport rate, bed surface composition and bed level changes were calibrated against previous estimates of average annual transport rate, sampled bed surface composition and surveyed bed level changes. The calibration adjustments involved altering the supply rate and grading of the gravel feed. No adjustments were made to the transport equations. After an initial period of “bedding-in” the model replicated observed bed level change and surface composition and the pattern of transport rate along the length of the river reasonably well. The model values of average annual transport rate were approximately 30-40% lower than estimates derived from previous gravel balance analyses.

This calibration result demonstrates that the model results can be applied with a reasonable degree of confidence.

Once calibrated, various scenarios were simulated in order to investigate the response of the river to different drivers. Key results of the scenario modelling are:

1. Gravel transport in the Ngaruroro is highly variable year to year (varying from one third to three times the average annual load in any given year).
2. There is significantly more inter-annual variability in the amount of gravel transported past Ohiti than past Fernhill.
3. Natural aggradation is occurring from Ohiti down to the limit of the gravel. The fastest aggradation is occurring around Fernhill and averages more than 30 mm/year.
4. The model shows some gravel does propagate downstream of the current limit of gravel on the bed but this is very variable over time and none propagates closer than 1.9 km from the sea.
5. If no extraction had taken place since 1977, bed levels would be one to two meters higher than they are now from Maraekakaho to Chesterhope.

6. Historic gravel extraction has not affected the total gravel supply rate into the extraction reaches.
7. Gravel extraction does reduce the propagation of gravel into the coastal reach. However, even with no extraction, no gravel propagates closer than 1.8 km from the sea.
8. Individual extractions influence bed levels within approximately 5 km upstream and downstream of the limits of the extraction.
9. It is possible to control aggradation between Maraekakaho and Ohiti with extraction downstream of Ohiti, but it is not possible to control aggradation downstream of Ohiti by upstream extraction.
10. Beach raking does significantly increase gravel mobility.
11. A 5% reduction in flow, as expected with future climate change, causes a 6-10% reduction in gravel supply into the extraction reaches.
12. A 0.8 m sea level rise causes aggradation of bed levels up to 15 km from the coast and reduction in sand delivery to the coast.

Morphological modelling generally has a high amount of uncertainty associated with it, but through careful use of historic data to calibrate/validate the model this study demonstrates the confidence that can be placed in the model results. Overall the morphological modelling has performed well, replicating historic river conditions and providing insight into the gravel transport processes in the Ngaruroro River. It is concluded that one-dimensional morphological modelling is a suitable tool for informing gravel management decisions on the rivers in Hawkes Bay Region.

1 Introduction

1.1 Background

The Ngaruroro River flows east from the Kaweka, Ruahine and Wakarara Ranges and discharges into Hawke Bay south of Napier. The lower reaches of the river are managed for flood protection with stop banks set back from the river fairway. Willow plantings are used to provide berm edge protection. Much of the lower river is braided, but downstream of Chesterhope Bridge the channel becomes single thread, and about 3 km from the coast the gravel ends. The section of river below Chesterhope Bridge was originally a man-made cut, and gravel has been slowly propagating into this reach since about 1965. Further detail on the Ngaruroro River and the flood protection scheme is given in “The Ngaruroro River Scheme” [Williams, 1987].

A long section of the Ngaruroro River is shown in Figure 1-1. The gradient of the river is initially around 0.5% but reduces downstream of Ohiti. As the gradient reduces the transport capacity of the river also reduces causing deposition.

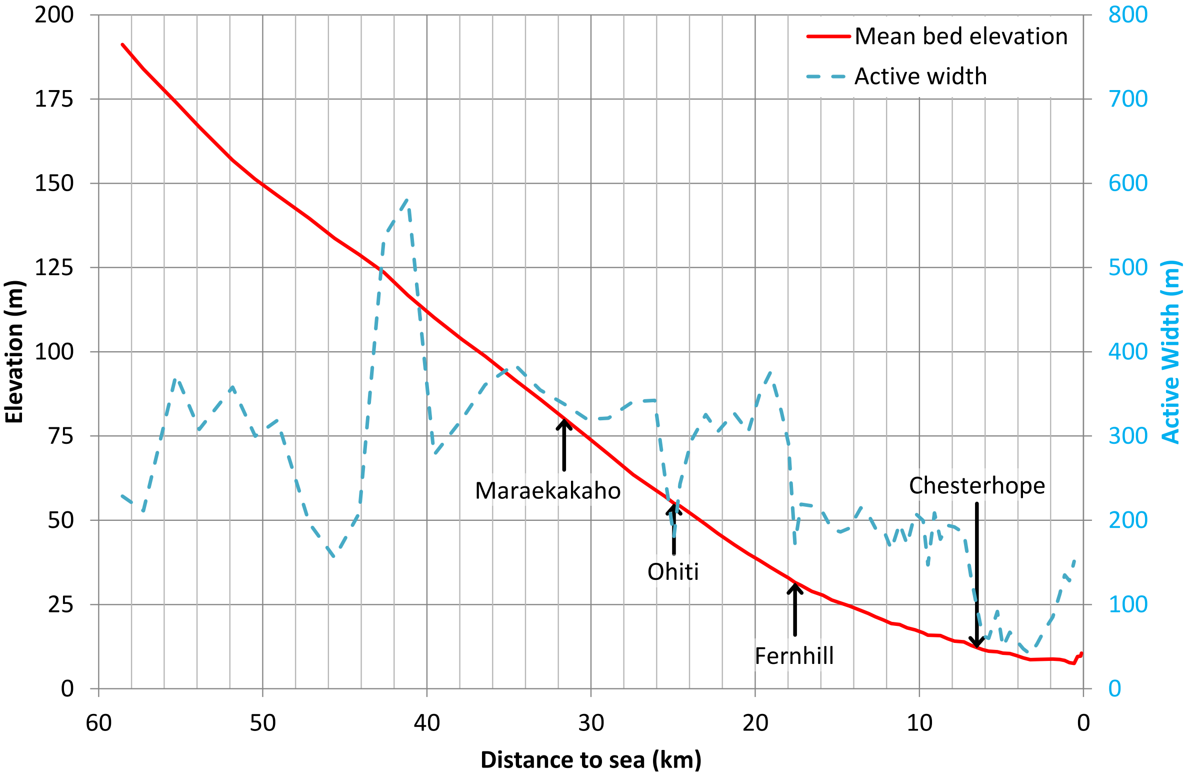


Figure 1-1: Mean fairway bed elevation and width on the lower Ngaruroro River.

Extensive gravel extraction has taken place on the lower reaches of many of the major rivers in Hawkes Bay in the last 50 years, including the Ngaruroro River. Gravel extraction serves the dual purpose of supplying gravel for construction and roading and managing bed levels and flood risk. Annual extraction from the Ngaruroro since 1961 is shown in Figure 1-2. Increasing demand for gravel has placed pressure on river gravel resources, particularly in the most easily accessible reaches. Demand for river gravel from the Ngaruroro currently exceeds supply.

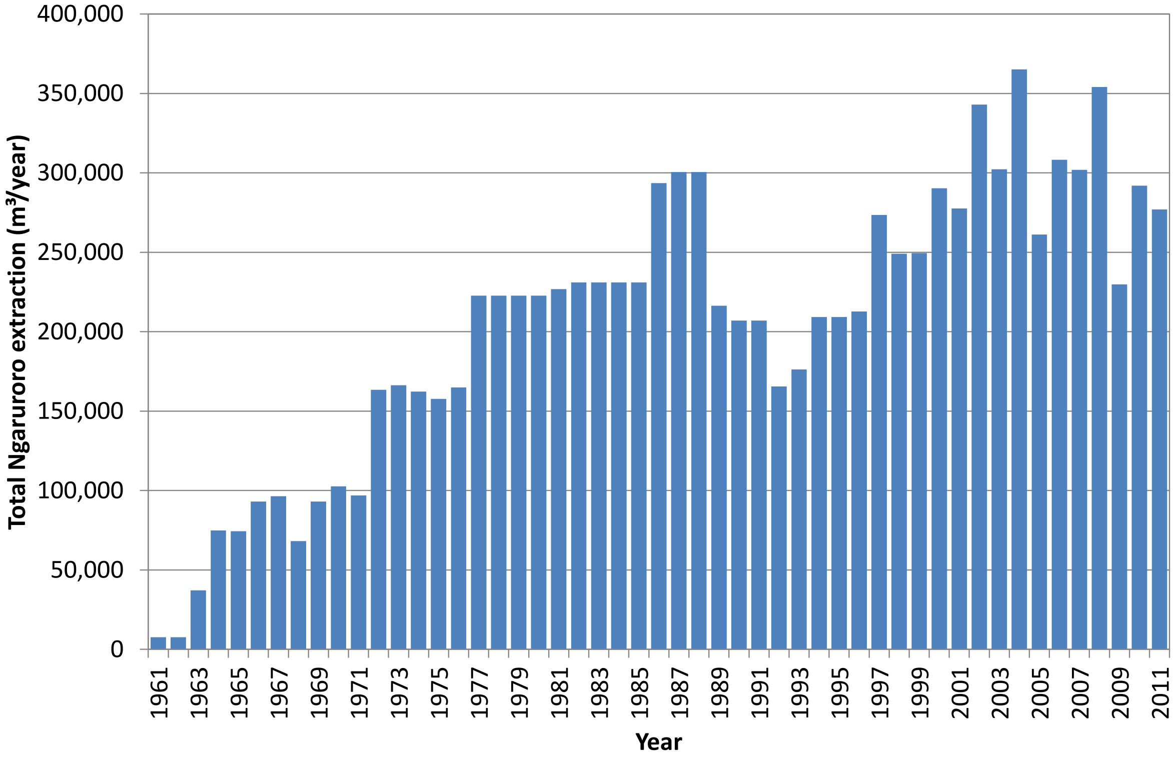


Figure 1-2: Annual Ngaruroro River gravel extraction, 1961-2011.

Hawkes Bay Regional Council is responsible for regulating gravel extraction through a consent process. In order to inform their management decisions they undertake regular (3 yearly) cross-section surveys and monitor mean bed levels with respect to a design grade line. The grade line has been designed to:

- maintain sufficient channel flood capacity to pass a design flood without overtopping
- limit berm edge heights to help prevent bank erosion and protect infrastructure such as bridges
- maintain a smooth channel slope.

In addition to allowing extraction equivalent to the volume of gravel above the grade line, the council allow extraction of a volume equivalent to that predicted to be deposited in any given reach. This deposition rate was estimated by previous analysis of gravel transport using a gravel balance approach [Williams, 1997, 1991; McBryde, 1989].

In 2010 the council initiated a review of the way in which it manages riverbed and coastal gravel resources in the Hawkes Bay region. As part of this review the need to improve understanding of gravel supply and transport processes was identified [Tonkin & Taylor, 2010]. A scoping study was undertaken in 2011 [Measures & Hicks, 2011], and this outlined a morphological modelling study as the best approach to gain an integrated understanding of the gravel budget, transport processes and bed-level change. Morphological modelling also provides a tool for understanding the impacts of different extraction regimes and investigating the impacts of possible future changes to extraction, climate and sediment supply.

1.2 Aims

This study aims to improve the understanding of the way in which the Ngaruroro River bed levels and gravel transport processes respond to different drivers. This understanding is important in order to be able to properly analyse the advantages and disadvantages of different extraction regimes and to defend decision making regarding extraction consents.

The second aim of the study is that it serves as a pilot study to inform the modelling of other rivers in the Hawkes Bay Region, particularly the Tukituki. The Ngaruroro River was selected to be modelled first for two reasons. Firstly, the river is an important supply of gravel and is subject to major gravel extraction. Secondly, there are aspects of the Ngaruroro River system which make it more straightforward to model, allowing accurate calibration and making it suited as a pilot study before applying the same technique to other more complex river systems such as the Tukituki. The Ngaruroro River is relatively straightforward to model because it has few major gravel sources in the modelled reach and at its downstream end the gravel does not reach the coast, enabling closure of the gravel budget at the downstream end.

This study uses one-dimensional (1D) morphological modelling to simulate the historic and future response of the Ngaruroro River morphology to different scenarios:

- historic extraction
- no extraction
- spatial and temporal impacts of specific extractions
- localised ceasing of extractions
- extra extraction
- beach raking
- changes in gravel supply
- climate change.

2 Modelling approach

2.1 Software

Gravel transport rates and bed level changes in steep braided rivers such as the Ngaruroro are complex, and modelling them presents a number of technical challenges. For this study it was decided to use a one-dimensional (1D) model because modelling the required length of channel (60 km) and time period (multi-decadal) using a two-dimensional (2D) model (with sufficient resolution to capture the sediment transport processes) is not feasible with current software and computing power (the run times would be far too long). Using a 1D model, however, introduces several limitations, including:

- 1D hydraulics (simple assumed flow distribution within cross-section; no cross channel flow; bend, expansion and contraction losses are not captured well)
- no lateral sediment transport (no bank erosion or cross-section shape changes)
- no variability in bed material across the cross-section and along the sub-reach represented by the cross-section.

It was decided to use the Gravel Routing And Textural Evolution (GRATE) software for this study. This software has been developed by NIWA and has a number of features that make it particularly suited to modelling gravel transport and bed level change on steep braided rivers. Key features of the software which were applied for this study include:

- **Multiple grain size fractions** – GRATE allows simulation of multiple grain size fractions, selective transport and bed armouring processes. The mixtures of grain sizes present in the Ngaruroro have varying mobility and respond differently to different river conditions. The grain size mixture can change spatially and temporally in response to different influences (floods, changes in supply, extraction).
- **Gravel extraction** – GRATE includes the capability to model time varying extraction around each modelled cross-section within the model. This capability is essential in order to include the effects of historic extractions and test the impacts of different extraction scenarios.
- **Distributed shear stress** – Most 1D sediment transport models only calculate a single mean shear stress at each cross-section for each time-step. GRATE has the option to estimate a shear stress distribution based on the distribution of water depths within the cross-section. This is particularly important for braided rivers where shear stress in the main braids can be much higher than elsewhere, resulting in varying transport rates across the cross-section. Using a shear stress distribution for each cross-section, rather than a simple mean stress, helps to address some of the limitations of a 1D model by implementing a pseudo-2D distribution of shear stress.
- **Advanced sediment transport formula** – Within GRATE some of the more recently developed surface-based transport formulas for mixed size sediment are available, such as the Wilcock-Crowe formula [Wilcock & Crowe, 2003] and

the Gaeuman et al. formula [Gaeuman et. al., 2009]. The advantages of these formulae are that they were derived by relating transport against surface-based measurements of grain size, which more accurately represents the bed properties of sediment exposed to the flow. Most multi-fraction transport models have been calibrated against bulk sediment size. Another advantage of these formulae is that they include hiding/exposure effects implicitly, without recourse to separate hiding functions.

- **Non-equilibrium bedload transport** – Non-equilibrium bedload transport accounts for the fact that actual transport is often different to potential or equilibrium transport at a given location and time due to the temporal and spatial lags between flow and sediment transport. In particular, because of the way bedload moves through braid/bar units in a braided river, sediment pickup is related to the length of a braid/bar unit. A good description of the difference between equilibrium and non-equilibrium transport models is given by Wu [2008].
- **Quasi-steady hydraulics** – GRATE has the option to use quasi-steady state hydraulics to accelerate run times for long simulations. This option allows time varying flows but assumes steady flow hydraulics at any given time. This simplifies the hydraulic calculations and allows much longer time-steps (by removing the Courant number limitation for solving the full 1D St Venant equations).
- **Separate form roughness and grain roughness** – In GRATE form roughness is specified and grain roughness is calculated using the Manning-Strickler equation applied to the D_{90} surface grain size. As the bed surface composition changes the grain roughness also changes due to the change in surface D_{90}.
- **Abrasion** – GRATE includes calculation of abrasion whereby with distance travelled gravel abrades to finer sizes and sediment mass is lost (to silt which travels as washload). Abrasion is calculated using the approach derived by Parker [1991A]. GRATE has the capability to route several lithologies with different abrasion susceptibility. However, the bed material of the Ngaruroro is predominantly greywacke, thus only a single lithology and a single abrasion coefficient were specified for the model.

A general outline of the solution process used in GRATE at each modelled time-step is shown graphically in Figure 2-1.

At each time-step of a simulation, the model:

1. Solves the 1D hydraulics for the specified input flow and downstream tide level to calculate water surface elevation and mean velocity at each cross-section.
2. Calculates the shear stress distribution within the active width of each cross-section based on the detailed cross-section shape, surface layer composition and 1D hydraulics.

3. Calculates the sediment transport rate and abrasion losses for each grain size fraction at each cross-section based on the shear stress distribution and the surface layer composition.
4. Updates the bed elevation and surface composition within the active width of each cross-section. These updates influence the hydraulic roughness and cross-section geometry for the hydraulic calculations at the next time-step. Bed changes are calculated based on the total transport rates in and out of the modelled reach represented by each cross-section. Any gravel extraction is included at this stage. Surface composition is updated based on the fractional transport rates. Material is moved to/from the base layer to maintain a constant surface layer thickness.

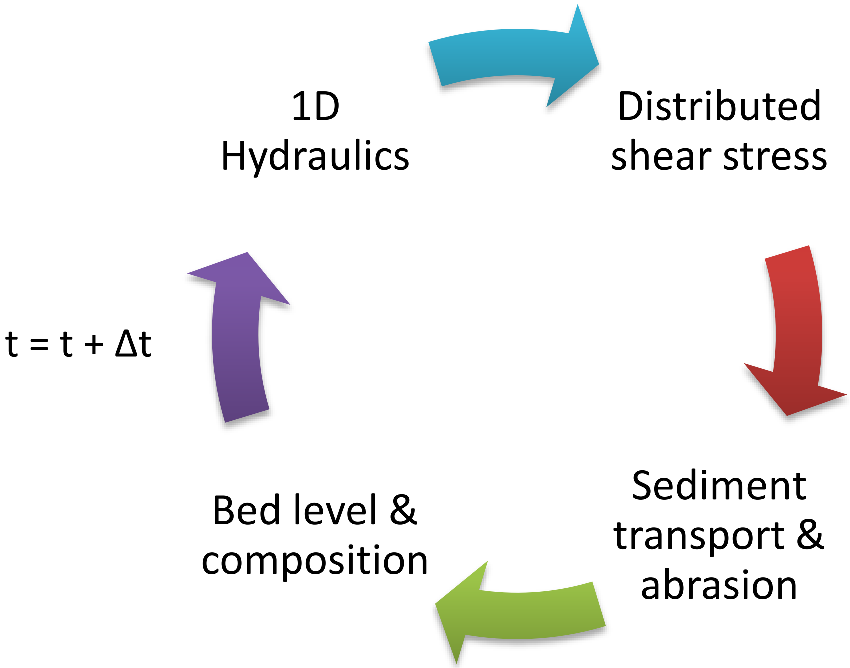


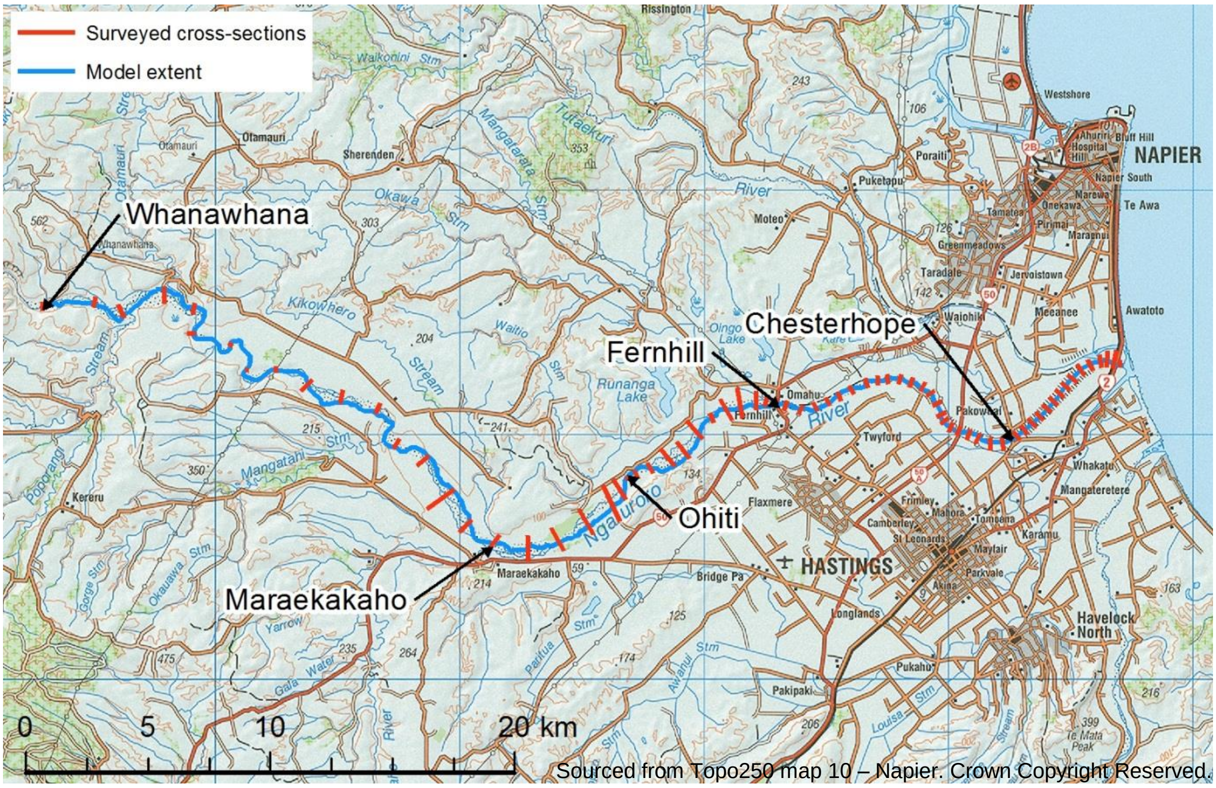
Figure 2-1: GRATE model calculation process at each time-step.

2.2 Ngaruroro River morphological model specifications

The GRATE model of the Ngaruroro River created for this study extends 58.5 km from Whanawhana Gauging Station to the coast. Figure 2-2 shows the extent of the modelled reach, the survey cross-sections and the named locations used in this report.

Thirty-five years of river flow, sediment transport and bed evolution were simulated based on historic data from the period 1977 to 2012. This period was selected because regular bed level surveys have been undertaken since 1977. Approximately 70 surveyed cross-sections were used to set up the model topography. The model was run with quasi-steady hydraulics using the distributed grain stress approach.

Inflows were included from the Upper Ngaruroro (upstream boundary), Poporangi Stream, Otamaui Stream, Mangatahi Stream, Maraekakaho River, Kikowhero Stream, Waitio Stream and Ohiwia Stream (Figure 2-2). The Tutaekuri and Clive Rivers were not included in the model as they only interact with the Ngaruroro downstream of the limit of the gravel. Gravel feed was included from the Upper Ngaruroro and Poporangi Stream only, as none of the other tributaries provide significant gravel input.



Sourced from Topo250 map 10 – Napier. Crown Copyright Reserved.

Figure 2-2: Ngaruroro morphological model extent and surveyed cross-section locations.

The model was calibrated hydraulically to observed peak flood levels measured during post flood surveys in January 2012 (575 m^3/s) and March 1988 (2020 m^3/s). The model was then calibrated to surveyed bed level change, previous estimates of bed load transport rate, and sampled surface grain size distribution.

3 Model input data

3.1 Cross-section surveys

Hawkes Bay Regional Council regularly survey 70 cross-sections on the lower 58.5 km of the Ngaruroro River as part of their three yearly regional program of cross-section surveys. Section spacing varies along the river, with the closest spacing in the lower reaches of the river (section spacing approximately 500 m) and progressively greater spacing further upstream (section spacing up to approximately 2000 m).

The morphological model constructed for this study was based on the 2010 cross-section surveys. Several modifications were carried out on the cross-sections during the model development:

- **Extending cross-sections:** In reaches which are not stop-banked, some cross-sections have low lying land adjacent to the river which can convey significant flows during floods. As part of work done by Craig Goodier in developing the Mike-11 hydrodynamic flood model of the Ngaruroro River, cross-sections were extended into these areas using data from the 2006 LiDAR survey.
- **Point thinning:** As many of the surveyed cross-sections contained hundreds of data points, they were thinned to a maximum of 100 points prior to model construction. Point thinning was carried out using an algorithm that removed the points that had the least impact on cross-section area. The overall impact on cross-section properties of this reduction in complexity was very small.
- **Cross-section alignment:** Several of the surveyed cross-sections are not aligned perpendicular to the river fairway. Due to the slope of the river, any misalignment can cause an artificial tilt in the cross-section where one berm appears high (because the survey has extended diagonally upstream on this bank) and the other berm appears low (because the survey has extended diagonally downstream). Also, the oblique alignment increases apparent cross-section area and so reduces mean velocity. Cross-sections were adjusted to correct for the angle between the surveyed cross-section and modelled cross-section (which is always perpendicular to the river fairway).
- **Berm adjustments:** Several cross-sections contained low spots in the berm areas that in reality would not convey significant flow (due to their short/unconnected extent in the streamwise direction). These cross-sections were manually modified to fill in localised low spots.
- **Active width:** The active width of cross-sections was identified based on the area of the bed with no vegetation or only immature vegetation – i.e. the area of the bed regularly mobile. Markers were added to the cross-sections in order to specify active width. The model only calculates transport across the active width and only adjusts bed levels within the active part of a cross-section.

- **Interpolation:** Due to the steep gradient on the Ngaruroro River it was necessary to interpolate the cross-sections to reduce model cross-section spacing to less than 200m.

The mean active bed level of the cross-sections was adjusted for both the hydraulic and morphological calibration runs in order to match the surveyed mean active bed elevation for the survey closest in time to the start date of the simulation (i.e. the date of the flood event for the hydraulic calibration and 1967 for the morphological calibration). It should be noted that only the bed elevation was adjusted as there is no way of simulating changes to cross-section shape within a 1D morphological model.

Downstream of surveyed cross-section 1 the river discharges through an outlet in the gravel barrier beach which separates the river mouth lagoon from the sea. The beach barrier and lagoon outlet channel are highly dynamic and change in response to sea level, wave conditions and river flow. In GRATE it is not easily possible to represent these changing conditions so a fixed outlet channel with geometry typical of river flood conditions was assumed.

3.2 Hydraulic roughness

Good information on hydraulic roughness was available from a calibrated Mike-11 flood model of the Ngaruroro constructed by Hawkes Bay Regional Council [Key contact: Craig Goodier]. In the GRATE model, hydraulic roughness is represented in two separate components: grain roughness and form roughness. Grain roughness is calculated from the surface sediment composition using the Manning-Strickler equation, and form roughness is specified for each cross-section. Form roughness can vary spatially across the cross-section.

In the Ngaruroro model different form roughness values were set for the active bed and the berms to represent the roughness differences due to vegetation on the berms. For simplicity, a single form roughness was specified for the whole width of the berms at each cross-section (although form roughness varies between cross-sections). The initial form roughness in the active bed was set so as to give the same total roughness as in the calibrated Mike-11 model. The form roughness on the berms was initially set based on observations of bank vegetation from aerial photography. Active bed and berm form roughness values were adjusted during hydraulic calibration to match observed peak water levels (see Section 4.1).

3.3 Bed sediment size

Gravel size sampling was undertaken on the Ngaruroro by Hawkes Bay Regional Council from January to March 2012. Surface sampling and sub-surface sampling were both undertaken at discreet locations along the river. In general it should be noted that the sustained high river flows experienced during the summer of 2012 restricted the sampling which could be undertaken as well as the ability to sample from within wetted areas of the bed.

Surface sampling was undertaken using the Wolman Count method on transects across the accessible parts of the active bed. Where possible, disturbed areas of the bed (due to extraction or beach raking) were avoided, but this was not always possible due to the extent of the disturbance along some reaches. The sampling transects included wetted areas of the channel where they were easily wadable but it is likely that the deepest and fastest flowing parts of the cross-sections are under represented in the samples. 15 separate samples were taken along the modelled section of the Ngaruroro, with 300 points recorded in each sample.

Data from limited previous sampling was also available. As part of investigations documented in the “Ngaruroro River Scheme: Investigations and Review” report [Williams, 1987] and the “Heretaunga Plains Gravel Resource Management Plan” [McBryde, 1989], surface samples representative of the full width had been taken at six locations. Other samples were also available for selective armoured parts of the bed but these were less useful for this study.

The surface size data was used to set the initial condition grain size distribution of the surface sediment layer (active layer) in the model. A long section showing the median grain size (D_{50}) and 90th percentile grain size (D_{90}) for the recent sample data and 1987 data, as well as the model initial condition is shown in Figure 3-1. In addition to setting the initial condition surface sediment composition, the observed surface grain size distribution was also used for calibration once the model had evolved the bed surface (see Section 4.2).

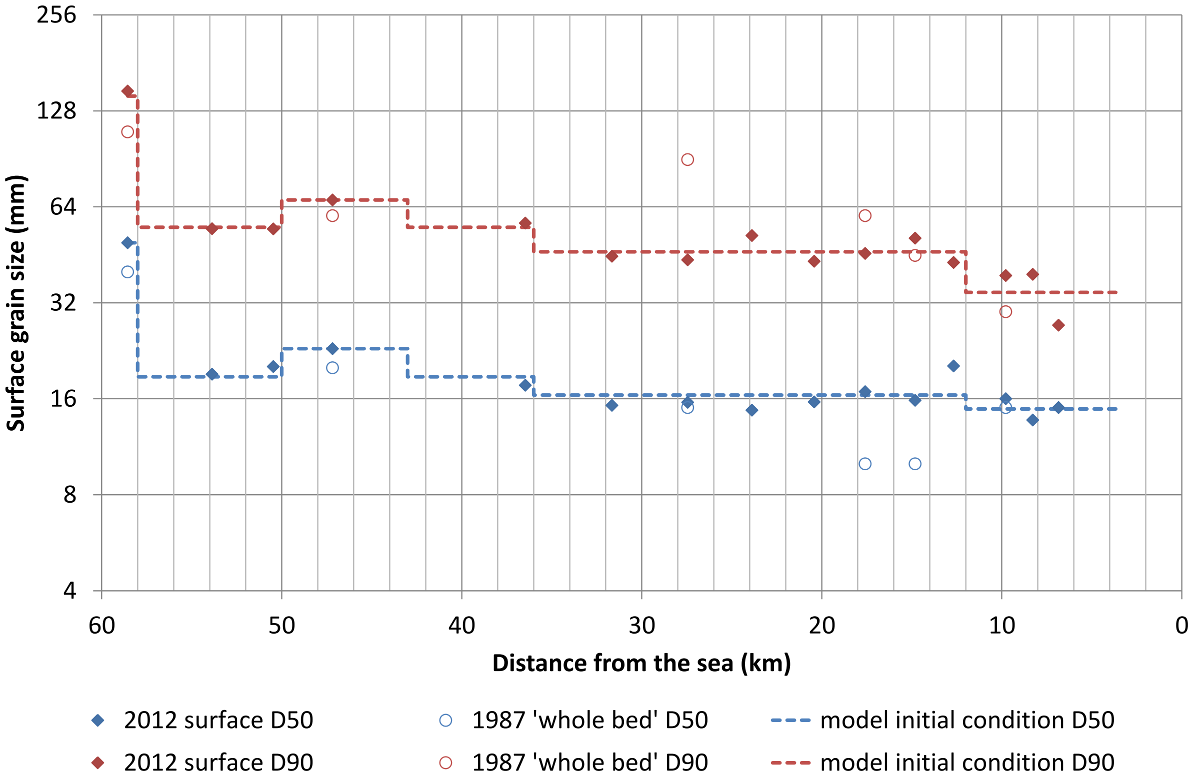


Figure 3-1: Long profile of sampled and model initial condition surface sediment D_{50} and D_{90}.

Sub-surface samples were measured at nine separate cross-sections on the Ngaruroro as well as two locations on the Poporangi Stream. Sub-surface sampling involved first clearing the surface armour layer from the bed, then digging a sample from a neat hole in the exposed sub-surface. The weight of each sample was such that the single largest grain in the sample weighed no more than 5% of the total. The sample was sieved on site down to 19 mm, and an approximately 5 kg sub-sample of the material finer than this was taken back to the lab for drying and further sieving. In order to account for spatial variability in sub-surface grain size distribution, 2-3 separate sub-surface samples were taken at each sampled cross-section.

The grain size distributions from the sub-surface sampling were used to set the model base layer composition. The model was divided into reaches of similar grain size distribution with breaks at locations where changes in channel slope, width or form occurred. A long section showing the median grain size (D_{50}) and 90th percentile grain size (D_{90}) for the sub-surface sample data and model base layer is shown in Figure 3-2.

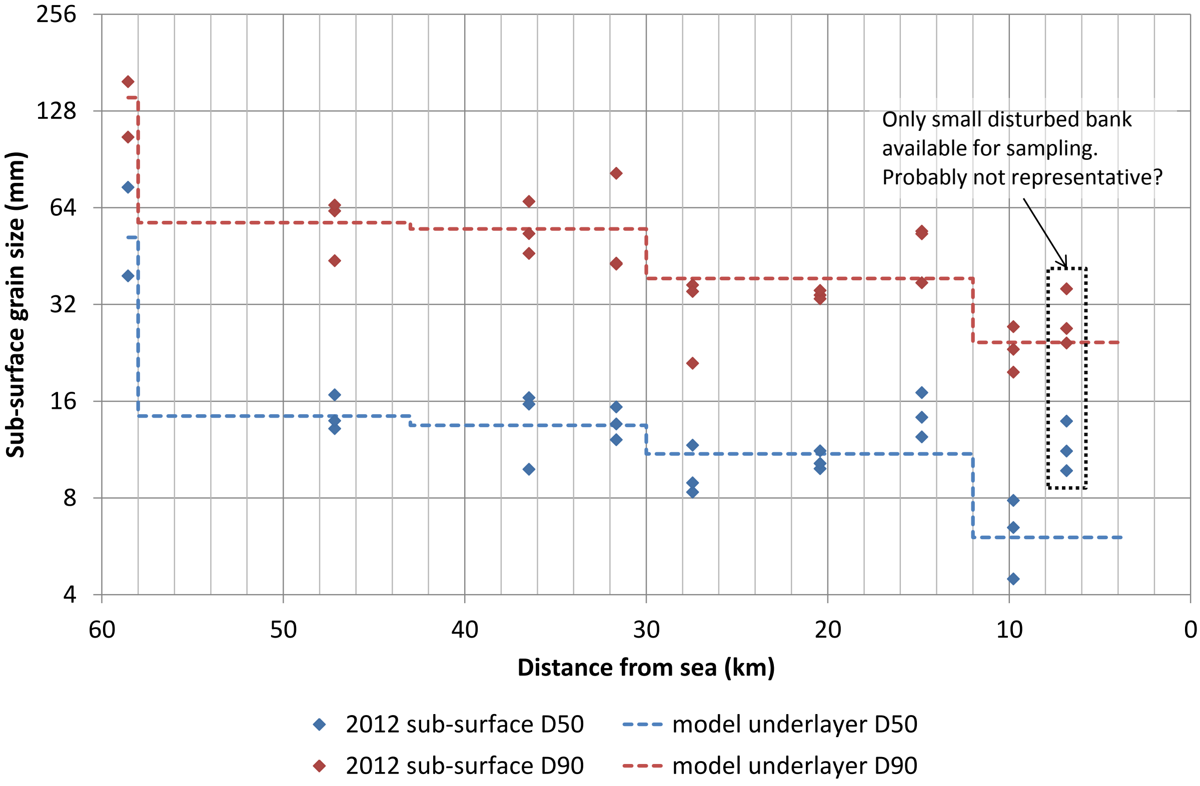


Figure 3-2: Long profile of sampled and modelled sub-surface sediment D_{50} and D_{90}.

Within GRATE, sediment composition is defined and tracked by recording the percentage of substrate and transported material within each of several discreet grain size fractions. For the Ngaruroro morphological model 13 sediment fractions were defined ranging from sand up to 181 mm. Sediment fractions were defined at half Phi intervals[1] for 4 mm and above and Phi intervals below 4 mm. The fractions and input compositions are shown in Table 3-1.

Downstream of the limit of gravel, within about 3 km of the coast, there is no sample data on bed sediment size distribution. As the focus of the modelling is on gravel transport it was felt that it was sufficient to assume a composition for this reach. The surface and sub-surface compositions were both set as 70% sand (less than 2 mm) and 30% very fine gravel (2 to 4 mm) for this reach.

---

[1] A Phi interval represents a factor of two; a half Phi interval is a factor equal to the square root of two.

Table 3-1: Model sediment fractions and base layer composition.

Grain size mm	Model base layer composition >58 km % Finer	58–43 km % Finer	43–30 km % Finer	30–12 km % Finer	12–5 km % Finer	<5 km % Finer
1.0	0.0	0.0	0.0	0.0	0.0	0.0
2.0	9.4	15.4	18.3	15.5	25.3	70.0
4.0	12.4	24.2	26.1	23.9	38.0	100.0
5.6	15.1	30.4	31.8	31.7	48.1	100.0
8.0	17.9	36.5	37.5	39.4	58.3	100.0
11.3	21.7	44.3	45.8	51.0	69.7	100.0
16.0	25.9	52.5	54.2	62.8	80.4	100.0
22.6	31.7	61.8	63.0	74.5	88.7	100.0
32.0	39.1	73.0	74.0	85.7	94.7	100.0
45.0	46.8	83.9	84.8	93.7	98.0	100.0
64.0	55.2	92.7	94.1	98.4	99.5	100.0
90.5	69.5	99.7	98.2	100.0	100.0	100.0
128.0	86.1	100.0	100.0	100.0	100.0	100.0
181.0	100.0	100.0	100.0	100.0	100.0	100.0

3.4 Sediment feed

Within the morphological model it is necessary to specify both sediment feed rate and composition. In reality, both the rate and composition of sediment supply would be highly variable, depending primarily on flow. For simplicity, it was decided to use a constant rate and composition of sediment supply in the model and use the upstream-most part of the model to generate a time varying feed to the lower reaches. The initial feed rate was set based on Gary Williams' [1997] estimated long term gravel transport rate of 170,000 m^3(bulk)/year (where 'bulk' volume includes voids), with 90% delivered from the Upper Ngaruroro (upstream of Whanawhana) and the remaining 10% from Poporangi Stream.

The sampled sub-surface grain size distribution at cross-section 70 (upstream model boundary on the Ngaruroro) and on the Poporangi Stream were used to set the initial sediment feed composition from these sources. During sediment calibration the upstream boundary composition on the Ngaruroro was adjusted so that the feed matched the composition of the transported bedload within the model (See Section 4.2). The final feed composition is shown in Table 3-2.

3.5 River flows

Time series of all significant flow inputs to the modelled reach were required for 1977 to 2012 in order to undertake the morphological calibration. In addition to this, suitable time series of future flows are required in order to undertake the scenario analysis. Griffiths and McKerchar [2012] investigated time series of annual maximum rainfall and river flow in the Hawkes Bay region in order to check for any trends or patterns which could affect the representativeness of different historical periods for forecasting future gravel transport. No evidence of any trend, periodicity or shift was found, nor any influence of the Interdecadal Pacific Oscillation, El Nino Southern Oscillation and Southern Annular Mode. These findings indicate that the historical time series of river inflows developed for the morphological calibration is suitable for forecasting future gravel transport under different scenarios.

Table 3-2: Model sediment feed composition.

Grain size mm	Sediment feed composition Ngaruroro % Finer	 Poporangi % Finer
1.0	0.0	0.0
2.0	17.3	21.0
4.0	21.8	28.8
5.6	24.0	34.0
8.0	30.4	39.5
11.3	42.1	47.7
16.0	57.8	56.0
22.6	75.0	66.3
32.0	88.8	80.5
45.0	96.4	90.5
64.0	99.3	96.4
90.5	99.9	99.4
128.0	100.0	100.0
181.0	100.0	100.0

Water level data is collected at monitoring stations on the Ngaruroro at Whanawhana, Ohiti, Fernhill and Chesterhope. Of these stations, both the Whanawhana and Fernhill gauging stations have reliable flow records for the full modelled period. Data from these stations was used to derive the model inflow boundaries.

Comparison of flows recorded at Whanawhana and Fernhill showed that the relationship between flows at the two gauging stations was complex, meaning it was not easily possible to divide the flows between the upstream model boundary and other tributaries whilst matching flows at both gauges. To simplify matters but maintain the recorded flow duration curve at both gauging stations, it was decided to scale the model upstream boundary off the recorded flow at Fernhill using a flow-varying scaling factor derived from the relationship between the flow duration curves at the two stations (see Figure 3-3). The minimum inflow was set as 10 m^3/s to ensure model stability. During low flows, flows recorded at Whanawhana are often higher than at Fernhill due to losses between the two gauging stations. As gravel transport rates are low during periods of low flow, it was assumed that this small additional flow in the upstream part of the model could be ignored with little impact on channel morphology. For this reason, the scaling factor for deriving the upstream boundary flow from the recorded flow at Fernhill was capped at 1.0.

The difference in flows between the upstream boundary flow and Fernhill recorded flow was distributed amongst the main tributaries entering the river between the two gauging stations. The distribution of the flows between the tributaries was assumed to be constant and was based on the distribution of mean flow according to the WRENZ catchment runoff model [NIWA, 2012A] (see Table 3-3). The tributaries were represented in the model as lateral flow boundaries.

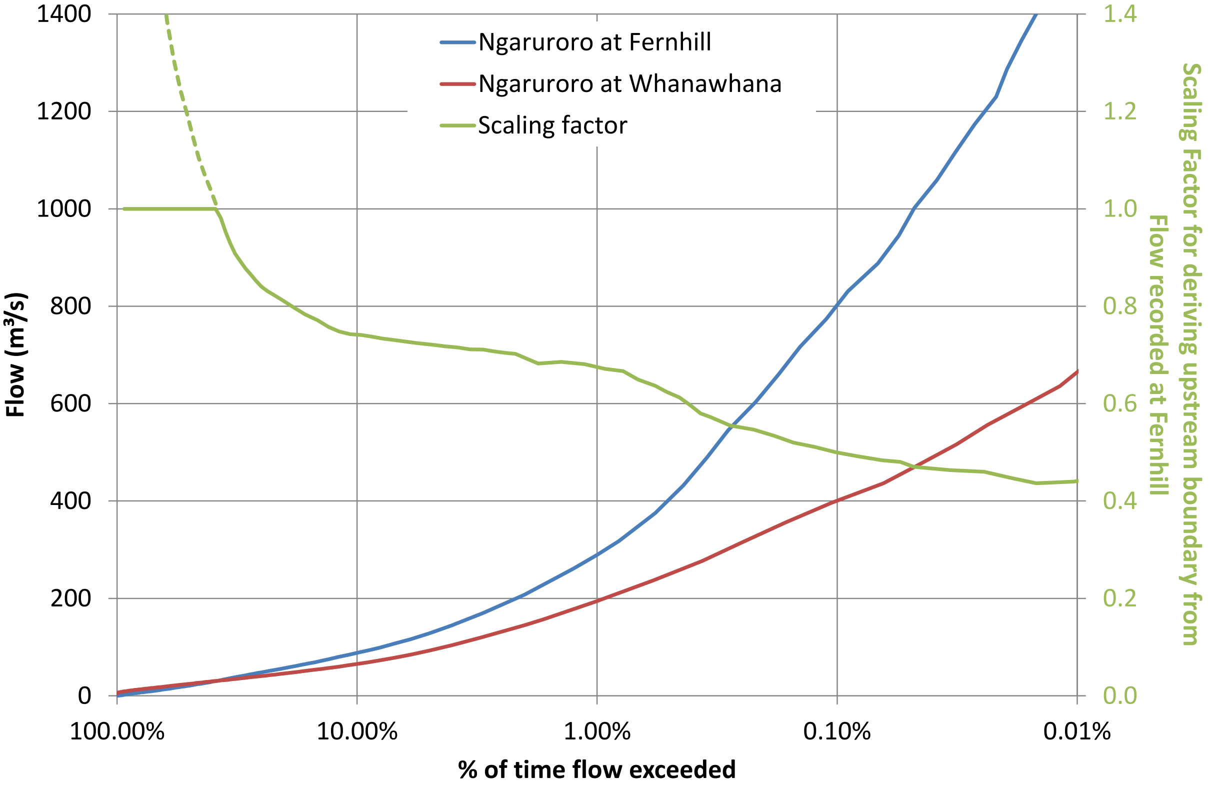


Figure 3-3: Flow-varying scaling factor for deriving model upstream boundary. Scaling factor calculated from the relationship between flow duration curves at Whanawhana and Fernhill.

Table 3-3: Distribution of flow between modelled tributaries. Tributary flows are scaled off the proportion of remaining Fernhill flow not input at the upstream model boundary.

Inflow	Location (km)	Mean flow (m^3/s)	Scaling
Tributaries between Whanawhana and Fernhill:			
Poporangi Stream	53.87	5.22	55.62%
Otamaui Stream	51.15	0.85	9.46%
Mangatahi	37.85	0.55	8.40%
Maraekakaho River	31.65	0.65	8.03%
Kikowhero Stream	31.37	0.50	5.33%
Waitio Stream	20.42	0.27	4.92%
Ohiwia Stream	17.98	0.73	8.23%
Tributaries downstream of Fernhill:			
Tutaekuri Waimate Stream	7.29	0.26	3.63%

For simplicity, the Tutaekuri and Clive Rivers were not included in the model. As these other rivers only interact with the Ngaruroro downstream of the limit of the gravel their effect is limited to their influence on the water levels in the lagoon behind the gravel barrier at the river mouth. There is already significant uncertainty in the modelled lagoon water level due to the varying nature of the outlet channel (see Section 3.1) so excluding the Tutaekuri and Clive does not generate much additional uncertainty.

3.6 Tide levels

Hindcast tide level data for the coast adjacent to the Ngaruroro River mouth was generated using the NIWA Tide Forecaster [NIWA, 2012B]. The forecast tide accounts for the astronomic tides only and does not account for the metrological effects on tide level. As the aims of the modelling are to simulate medium term (years to decades) gravel transport and bed level change it was felt that the astronomic tides alone were sufficient.

3.7 Historic extraction

Data on historic extractions were compiled from extraction returns and previous reports. Extraction data were compiled into a yearly extraction time series for each cross-section. For some data, particularly early records, it was necessary to make assumptions regarding the exact location of extractions. When lacking information to link the extractions to specific cross-sections, the extractions were distributed over likely reaches based on the area of bed associated with each cross-section in the model (active width multiplied by cross-section spacing). The compiled extraction data is presented by year in Figure 1-2 and by location in Figure 3-4.

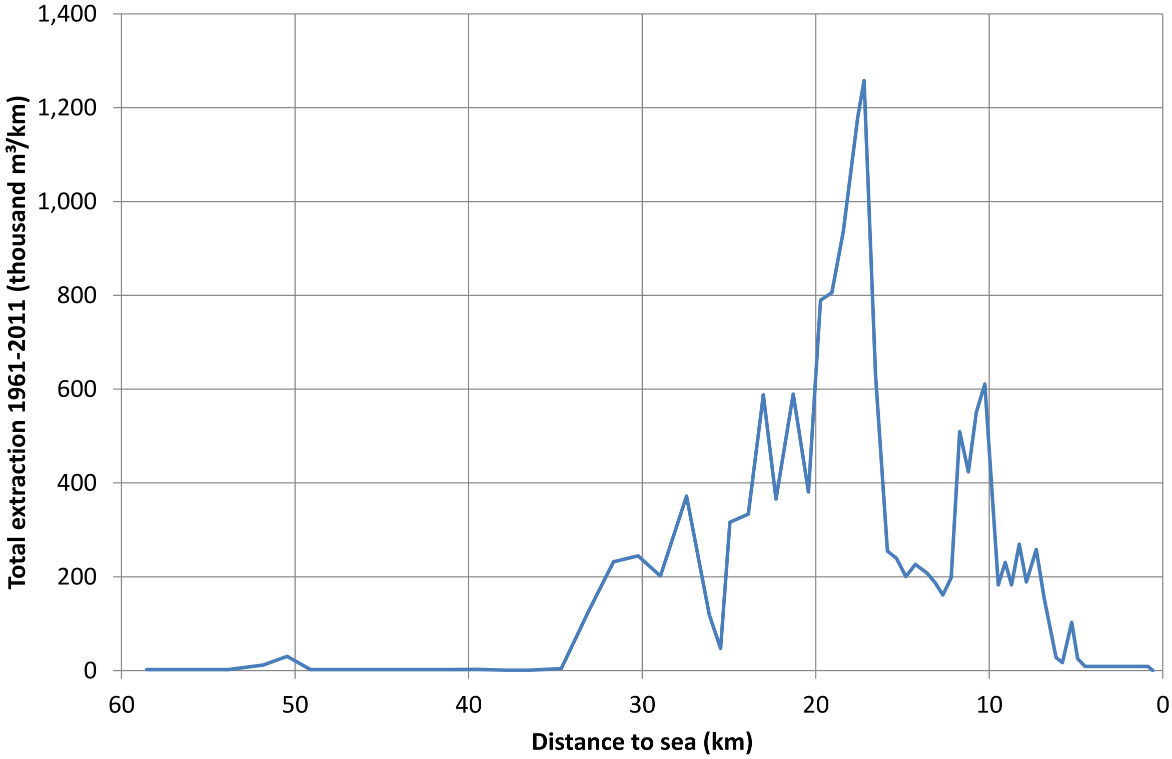


Figure 3-4: Distribution of total historic extraction along the length of the Ngaruroro River.

From the complied extraction data, time series of extraction rates were produced for every model cross-section. In reality, extraction at any given cross-section would only occur for relatively short periods of time within any given year, making it more of a step change in bed level/surface composition than a gradual event. However, there is insufficient information to include this level of detail in the model so each extraction was assumed to occur at a continuous (low) rate for the whole of the year it occurred, rather than at specific dates within the year.

3.8 Beach raking

Beach raking is undertaken using a large tractor towing a seven leg implement penetrating 900 mm into the river bed. Beach raking is carried out on exposed gravel bars to increase gravel mobility and control vegetation.

Information on historic beach raking was compiled from Hawkes Bay Regional Council staff. Raking takes place annually in March-April in two reaches of the Ngaruroro: cross-section 16-18 (6.84-7.86 km) and cross-section 50-58 (27.44-39.56 km). Outside of these two reaches occasional raking is undertaken as necessary to control excessive plant growth or where armoured islands have formed which are not accessible to gravel extractors.

In order to simulate beach raking, an experimental feature of GRATE was developed which mixes the surface and sub-surface sediment layers to a user specified depth. This mixing changes the surface layer composition in the model which influences the bed mobility. In reality, beach raking also loosens the bed which probably further increases mobility. This loosening effect cannot currently be simulated in GRATE. Within the Ngaruroro model only the annual raking was considered as there was insufficient information on extent and timing of the occasional raking to accurately consider it. Raking was assumed to occur on 1 April every year and was assumed to cover 60% of the bed width and mix the gravel to a depth of 900 mm.

3.9 Other model input parameters

A summary of the model input parameters is given in Table 3-4. Further detail on the selection of values for the most important parameters follows the table.

Table 3-4: Model input parameters for Ngaruroro GRATE model.

Keyword	Description	Value
MAX_DT_QS	Maximum time-step during quasi steady simulation	3600 s
CDT	Measure of permissible bed level change within one time step. Bed level change greater than this will result in a reduction in time step.	0.001 m
LA	Active layer thickness (bed surface layer)	0.15 m
NBS	No of layers below the initial surface	1
PORO	Porosity of sediment deposits	0.4
NEQAL	Bedload non-equilibrium adaptation length	600 m
DK	Roughness height / D90	1.5
THETA	Spatial weighting coefficient in hydrodynamic solution scheme	0.6
THETA_S	Spatial weighting coefficient in sediment transport solution scheme	0.8
PHI_S	Temporal weighting coefficient in sediment transport solution scheme	1.0
-	Abrasion coefficient	0.000005 m^{-1} (0.005 km^{-1})
QSFACT	Sinuosity factor	0.86 - 1.00 (see below)
ComputeST	Compute sediment transport (On/Off = 1/0)	1
UpdateBedMorphology	Bed updating (On/Off = 1/0)	1 (except hydraulic calibration)
HDComputation	Hydraulic computation	1 (Quasi-steady)
STEqn	Sediment transport formula	3 (Gaeuman, Trinity River Calibration)
STComputation	Sediment transport computation	1 (non-equilibrium)

Sediment transport formula: The Gaeuman et al. [2009] sediment transport formula with Trinity River calibration was selected for use in this study. The formula is based on the Wilcock-Crowe [2003] sediment transport formula but adopts a dimensionless reference grain size that is calibrated against field data from the Trinity River (USA). This formula was selected because:

- it is a surface-based transport formula
- it is calibrated to field data
- it has been successfully applied to 1D morphological modelling of 70km of the Waimakariri River [Measures, 2012] as well as 2D event scale morphological modelling of the Lower Waitaki River [Hicks et al., 2011], Crossbank reach of the Waimakariri River, and the Rees River in Otago [Williams et al., in preparation].

Bedload transport scaling factor to account for sinuosity: A scaling factor was assigned to each cross-section based on the sinuosity of the channels in that reach. This factor accounts for the difference in path length between the braids and the overall river, and scales the sediment transport down accordingly (because the sediment is actually travelling further than the straight line distance between the cross-sections suggests). Sinuosity factors were derived for different reaches based on measurements of path length from aerial photography. The sinuosity factors applied in the model are shown in Table 3-5.

Table 3-5: Bedload transport scaling factor applied to model reaches. Factor accounts for difference in path length between braids and fairway.

Cross-sections	Chainage	Scaling factor
1 to 16	< 7.0 km	1.00
17 to 38	7.0 to 17.7 km	0.94
38a to 59	17.7 to 42.0 km	0.91
60 to 65	42.0 to 51.0 km	0.92
66 to 70	> 51.0 km	0.86

Non-equilibrium adaptation length: The non-equilibrium adaptation length is a parameter of the non-equilibrium bedload transport approach described in Section 2.1. The adaptation length in braided rivers is related to the length of a typical braid/bar unit. The length of braid/bar units in the Ngaruroro varies along the length of the river depending on factors such as its slope and confinement. It is currently not possible to specify a spatially varying non-equilibrium adaptation length within GRATE so it was necessary to estimate a ‘typical’ length for the whole river. The non-equilibrium adaptation length was set as 600m for the Ngaruroro model.

Abrasion coefficient: There is high uncertainty over the selection of an appropriate abrasion coefficient. Parker [1991B] gives abrasion coefficients for granite (0.0003 km^{-1}) and limestone (0.01 km^{-1}). It is expected that the Ngaruroro greywacke would fall between these limits. Adams [1978] investigated the abrasion coefficients of many New Zealand river and beach gravels including different sources of greywacke. Unfortunately, Adams did not investigate any Hawkes Bay greywacke. He found that experimental abrasion coefficients for *sound* Triassic greywacke pebbles were in the range 0.00052 km^{-1} to 0.0023 km^{-1} and *unsound* pebbles had coefficients up to 0.012 km^{-1} (*unsound* pebbles are initially weathered, inhomogeneous, angular or fractured). He notes that natural abrasion rates of pebbles in rivers are likely to be 3 to 10 times higher than experimental rates as they can wear in place by the passage of other pebbles. Marshall [1927] investigated the abrasion of Napier beach gravel and found experimental abrasion rates of 0.00026 km^{-1} to 0.00052 km^{-1}.

Initially the abrasion coefficient was set as 0.001 km^{-1}, a typical value for greywacke from Adams' 1978 paper. This abrasion coefficient was found to be too low during the morphological calibration and was increased to improve model calibration. The final abrasion coefficient used for the scenario modelling was 0.005 km^{-1}. This final value is within the range of expected values, especially given that natural abrasion rates may be significantly higher than experimental rates.

Active layer thickness: Active layer thickness was set as 0.15 m based on the largest grains commonly found on the bed. This is also approximately two times the typical 90th percentile surface grain size (D_{90}), another common guidance value for active layer thickness.

Relationship between roughness height and grain size for the calculation of grain stress: GRATE calculates grain stress using a Nikuradse roughness height (k_s) based on the surface grain size distribution. A wide variety of relationships ranging from $k_s = 1.23D_{35}$ to $k_s = 3.0D_{90}$ are suggested in the literature (see Table 2-1 in Sedimentation Engineering [Garcia, 2008] for a comprehensive summary). For this study it was decided to use $k_s = 1.5D_{90}$ as this has been found to give successful model calibration in previous studies of similar rivers [e.g. Measures, 2012].

4 Calibration and validation

4.1 Hydraulic calibration

Peak flood level data was available for various past flood events. The available data covered a range of different magnitude floods and for each event data was available along different river reaches.

Two flood events were used for hydraulic calibration (see Table 4-1). The two events selected represented quite different magnitude flood events and both had data available at a large number of cross-sections. The surveyed peak level data for many of the other flood events only covered shorter reaches of the river.

Table 4-1: Hydraulic calibration event details.

Date	Peak discharge (Fernhill) m^3/s	Number of surveyed levels	Extent of surveyed levels
8 January 2012	575	23	5.25 km to 51.84 km (XS13 to XS66)
9 March 1988	2020	51	0.57 km to 26.13 km (XS1 to XS49)

During hydraulic calibration the form roughness of the active channel and the berms was modified to improve the fit between observed and modelled peak water levels. In particular the form roughness was increased at the bridges to represent the additional losses associated with obstruction caused by the bridge piers. The residual differences between the observed and modelled peak water levels following calibration is shown in Figure 4-1.

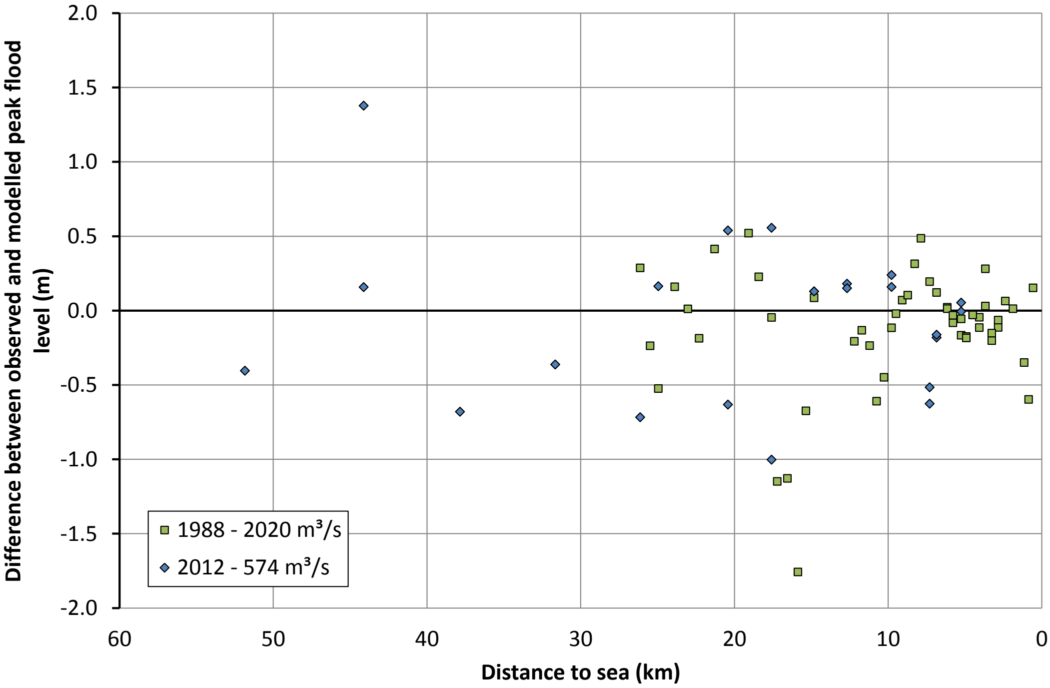


Figure 4-1: Residual differences between observed and modelled peak water levels. At some cross-sections more than one water level was surveyed (e.g. left bank, right bank). At these locations separate points are used to represent the separate water levels.

In general, the calibration is reasonable with over 90% of observed levels within 1 m of the modelled average water level and 75% within 0.5 m. The residual differences reflect a variety of causes including:

- Variability in water level across a cross-section. In reality, the water level varies across the width of the cross-section and the surveyed level may not be representative of the mean level at that cross-section. This is indicated by the fact that where observed water levels were recorded at both left and right banks of a cross-section there were differences of up to 1.56 m in recorded water level. At the three cross-sections where both left and right bank levels were recorded upstream of 15 km during the 2012 event all had differences in water levels across the river of greater than 1m.
- Inaccuracy in identification of peak water level. Peak water level can be very difficult to identify accurately during post flood surveys.
- Cross-section shape and bed level effects. Although mean active bed level was adjusted to the mean active bed level taken from the survey closest to the date of the flood, the mean level and cross-section shape may have been significantly different at the time of the flood. In particular, the cross-section shape during the 1988 event is unlikely to be well represented by the model cross-sections (with shape from the 2010 survey adjusted to the elevation of the 1988 survey).

4.2 Morphological calibration

Morphological calibration was undertaken by simulating the 35 year period from 1977 to 2012. The performance of the model was assessed by comparing modelled and measured:

- bed level change
- gravel transport rate
- surface grain size distribution.

During calibration, some of the most uncertain inputs were adjusted to improve performance of the model but the main sediment transport equation and shear stress calculation parameters were left unchanged. These parameters were found to work well on the Waimakariri River morphological model [Measures, 2012] and are the same as those used when the sediment transport model was originally calibrated to field observations on the Trinity River. Without identifying specific reasons that the Ngaruroro river sediment should behave differently from the Waimakariri it is difficult to justify changes to the transport formula. By keeping these parameters fixed the final calibration result is effectively a validation of the model performance.

The parameters that were calibrated in order to improve the fit of the modelled and observed conditions in the river were:

- Abrasion coefficient – the abrasion coefficient was increased, which had the effect of reducing the grain size in the lower reaches of the river and increasing the mobility of the bed.

- Sediment feed composition – during initial model runs, rapid coarsening of the bed surface was experienced, likely due to the sediment feed composition being too coarse. To correct this, the feed composition was set equal to the average composition of the modelled bedload transport for the first year of the simulation. This helped prevent the bed surface from over-coarsening and increased the transport rate.
- Sediment feed rate – the sediment feed rate was adjusted (reduced) to prevent excessive aggradation in the upstream part of the model.
- Beach raking – It was not originally intended to simulate gravel raking during the morphological calibration runs as its implementation in GRATE is experimental. However, during calibration it was found that the model results were showing consistently coarser surface sediment size distributions than observed in the field. The inclusion of beach raking in the model was found to significantly reduce surface grain size and increase transport rates, suggesting that beach raking does indeed have significant impacts on gravel transport and that its experimental inclusion in the model is reasonably effective. It was decided to include it for the final calibration. The impacts of raking on the model results are described in Section 5.2.6.

The following paragraphs and figures show the fit between the simulated and measured data. In general, apart from the first few years of simulation, the calibrated model compares well against the measured data. The only exception to this is that the model under-represents transport rates by approximately 30% compared to rates estimated from gravel balance analysis. The initial period of simulation (1977 to approximately 1981) performed poorly and the reasons and implications of this are discussed at the end of this section.

Gravel transport rates have been estimated previously in various studies using a gravel balance approach [Williams, 1997, 1991; McBryde, 1989]. Figure 4-2 shows a comparison of the previous estimates. These estimates have all been derived by first assessing the volume of bed change between different survey periods based on the mean fairway bed level change, the fairway width and the distance between cross-sections. The gravel balance analysis is then calculated by working upstream from an assumed zero transport rate at Chesterhope and summing the inputs and outputs from each river reach including extraction and the change in stored volume.

The main cause of the differences between the previous estimates is that they are based on analysis of different time periods. Williams [1997] notes that prior to 1981 the reach upstream of Ohiti was congested by willows, but since then a cleared fairway has been maintained allowing increased transport rates in this reach. This is reflected in the difference between the 1977-85 and 1985-93 estimates of transport rate at Ohiti.

It should also be noted that the previous estimates are sensitive to the fairway width selected for analysis of bed level change. The result of this sensitivity is that the results from different time periods are not consistent with each other as the base date for selection of fairway width varies.

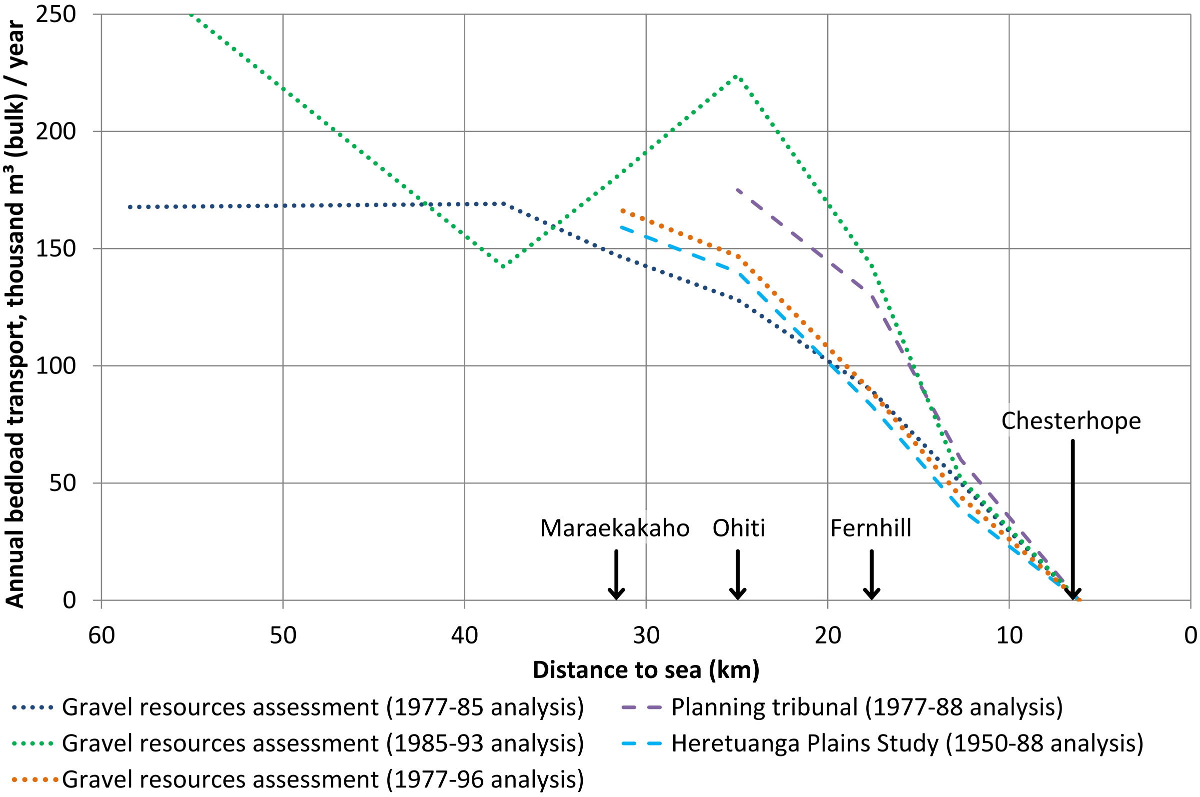


Figure 4-2: Previous estimates of gravel transport rate using a gravel balance approach. Plot includes data from Ngaruroro River Gravel Resources Assessment [Williams, 1997], Planning tribunal [Williams, 1991] and Heretaunga Plains Study [McBryde, 1989].

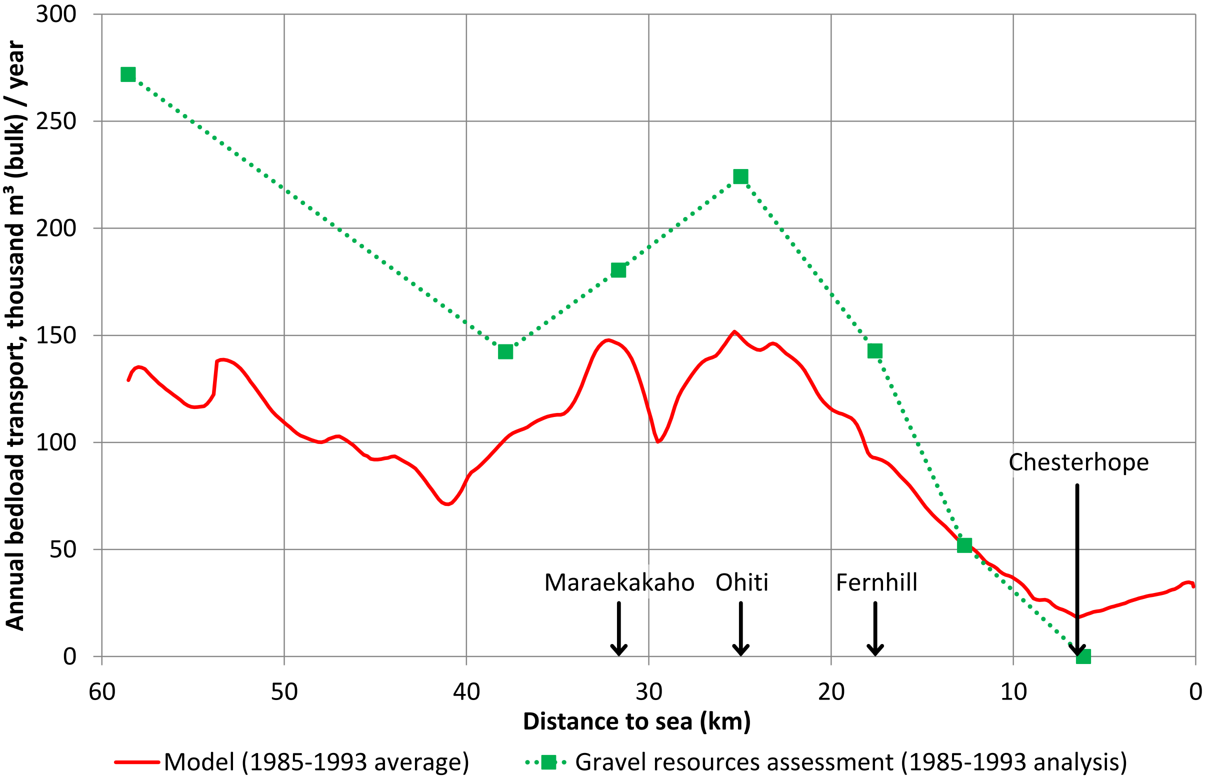


Figure 4-3: Model transport rate and rate estimated from gravel balance approach for 1985-1993 period.

Given that the model represents the modern channel geometry (with cleared and maintained fairway) the best estimate for comparison against the model results is the analysis of the 1985-1993 period reported in the Ngaruroro River Gravel Resources Assessment [Williams, 1997]. A comparison of the modelled transport rate for 1985-93 with the estimate from the same period is shown in Figure 4-3. The figure shows that the model calculates a transport rate 30-40% lower than the previous estimate for the majority of the modelled reach but that the shape of the spatial variations in transport rate compare well. In particular, the increase in transport rate from 38 km to Ohiti, and the reduction in transport rate from Ohiti down to Chesterhope matches the shape of the estimated transport rate very well.

The upstream part of the model (upstream of 50 km) is influenced by the constant rate sediment feed at the model boundary. As the constant rate was set equal to the long term average this restricts the transport rate for the upstream-most part of the model during years of higher than average transport (e.g. 1985-1993) and raises it for below average years.

Downstream of Chesterhope the model shows a residual transport rate despite the fact there is no gravel on the bed. This transport rate is representative of sand rather than gravel and should not be considered accurate as the composition of the underlying bed material downstream of the gravel limit was only assumed, due to the lack of sample data. The gravel balance analyses all assumed a zero transport rate from the limit of the gravel downstream.

Surface grain size distribution data was available from the Wolman counts undertaken by Hawkes Bay Regional Council (see Section 3.3). Figure 4-4 shows a comparison of the modelled and sampled surface grain size. The modelled grain size is an average of the final year of simulation (the averaging smoothes out variability caused by floods and beach raking).

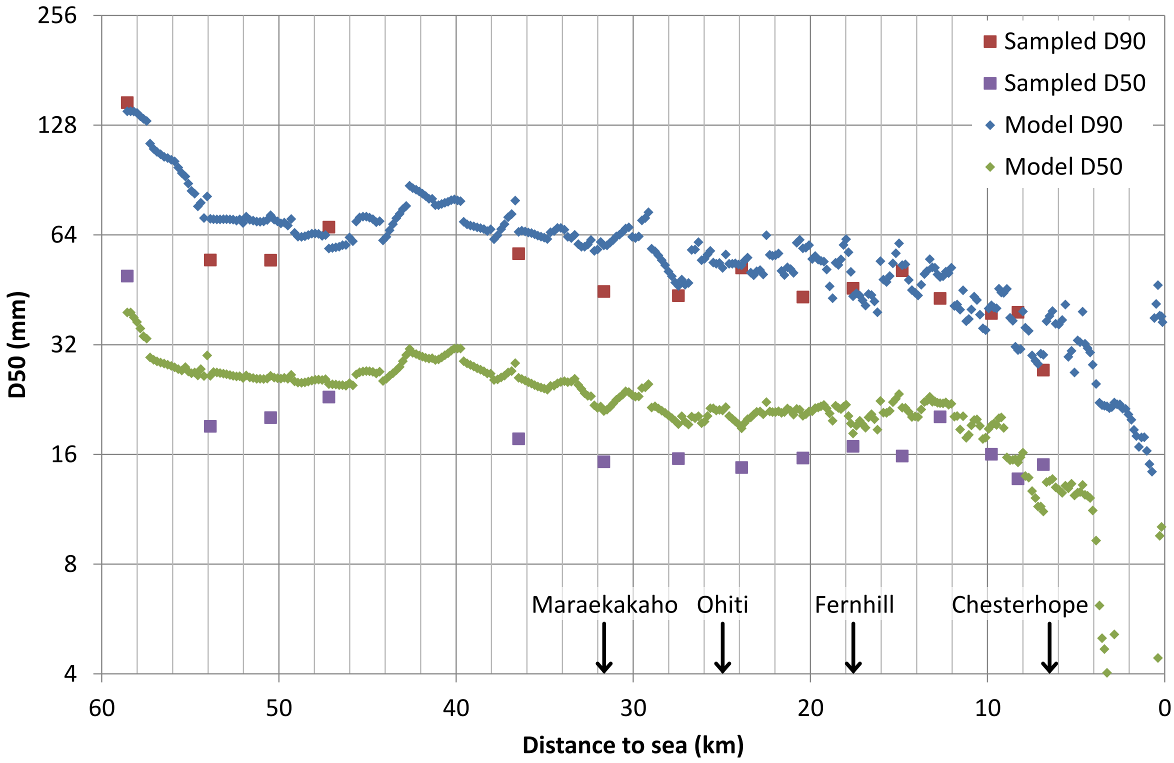


Figure 4-4: Modelled and sampled median and 90th percentile surface grain size (D_{50} & D_{90}). Model D_{50} and D_{90} values represent the average for the final year of simulation.

The model results fit the sample data reasonable well, but it is notable that the model surface is consistently coarser than the sample data upstream of Fernhill. The slight over-prediction of the surface grain size distribution is consistent with under-prediction of the transport rate (i.e. a coarser bed is likely to have a lower transport rate).

However, it should also be noted that there are two possible causes of bias in the sample data towards finer grain sizes: (1) the inability to sample within the deeper areas of the braids; or (2) by sampling in the late summer when many areas have been disturbed by extraction or raking. This second point was investigated further by comparing the minimum D_{50} and D_{90} for each model cross-section in the last year of simulation (rather than the average) with the sample data (see Figure 4-5). This comparison shows that the finest surface compositions seen in the model during the last year are very close to the sampled compositions. This suggests that temporal variability in surface sediment composition is likely to be a partial cause of the differences between the modelled and sampled grain size, although it is unlikely to explain the whole difference. This is consistent with the biggest differences being in the reaches where the majority of ripping and extraction takes place.

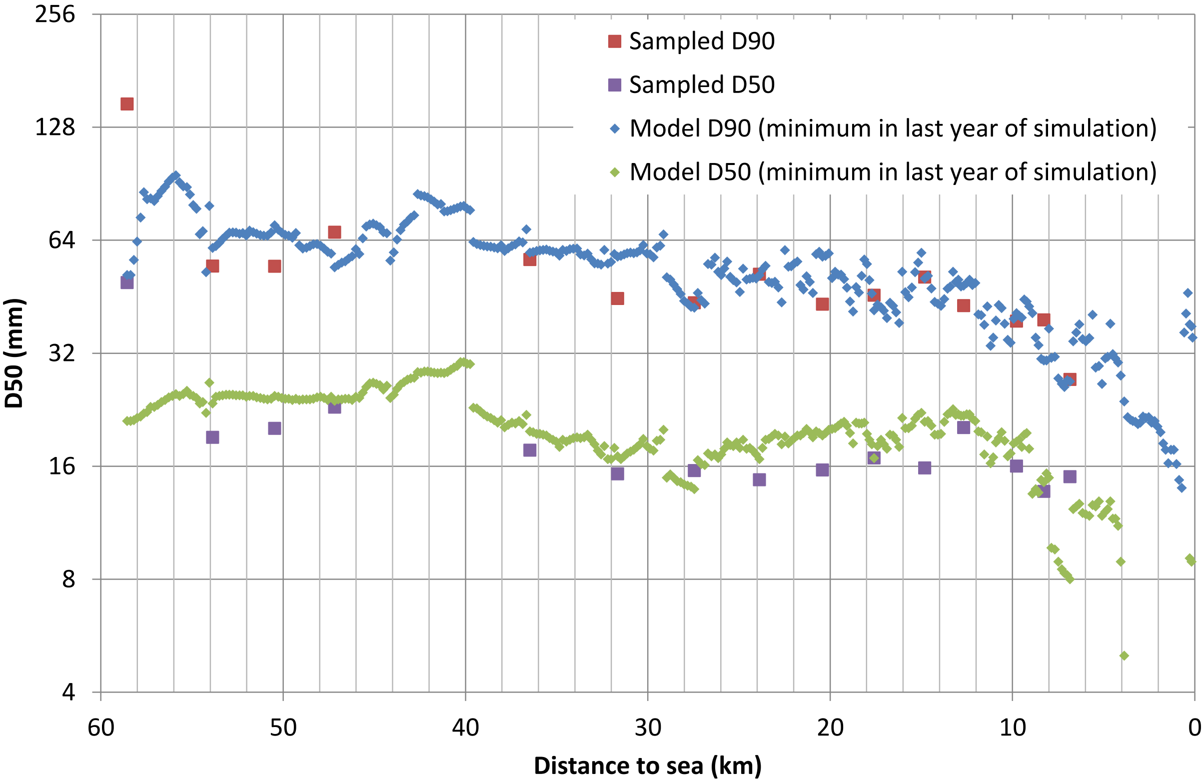


Figure 4-5: Comparison of minimum D_{50} and D_{90} in last year of model simulation with sampled D_{50} and D_{90}.

Gravel has been propagating into the downstream reach of the Ngaruroro River since the full flow of the river was diverted into the current channel (a man-made cut) in approximately 1965. The distance gravel has propagated through this channel is another useful check on model performance. The 1987 Ngaruroro River Scheme Investigations and Review report [Williams, 1987] stated that gravel had propagated to cross-section nine (3.67 km from the sea), approximately half way down the cut. Currently, gravel is easily visible to cross-section twelve (4.91 km from the sea) and is present on the bed to at least cross-section nine although there is not much gravel of significant volume below this point (Gary Clode, pers. Comm. September 2012).

The position of the gravel-sand transition in the model is shown in Figure 4-6. For the morphological calibration it was assumed gravel extended up to 4.5 km from the sea in 1977 (the start of the simulation). The model results show good agreement with the observed gravel extent. In the model, gravel rapidly propagates down the cut to approximately 3.7 km from the sea, consistent with the observed gravel extent in 1987. Once the gravel bed extends to this location it ceases to consistently propagate further. Occasionally a small amount of gravel is transported downstream and deposited but it is subsequently buried by sand or transported through to the coast. The volume of gravel reaching the coast is very small.

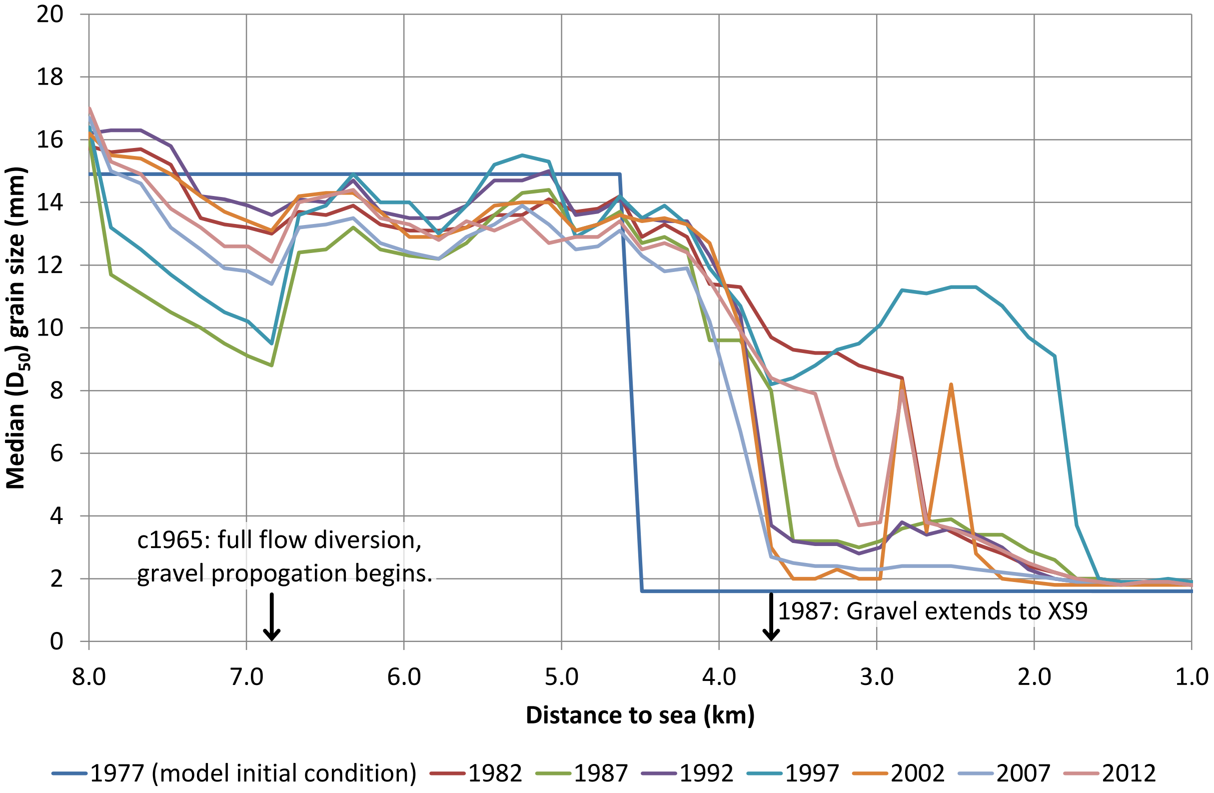


Figure 4-6: Position of gravel-sand transition in model, 1977-2012.

Information on actual bed level change was available from the 3 yearly cross-section surveys undertaken by Hawkes Bay Regional Council (see Section 3.1). The mean fairway bed level was extracted from the historic cross-sections using the same active width as specified in the model. The relative bed level change between different surveys was compared with the model results for different periods. Figure 4-7 shows a comparison of the surveyed and modelled bed level change.

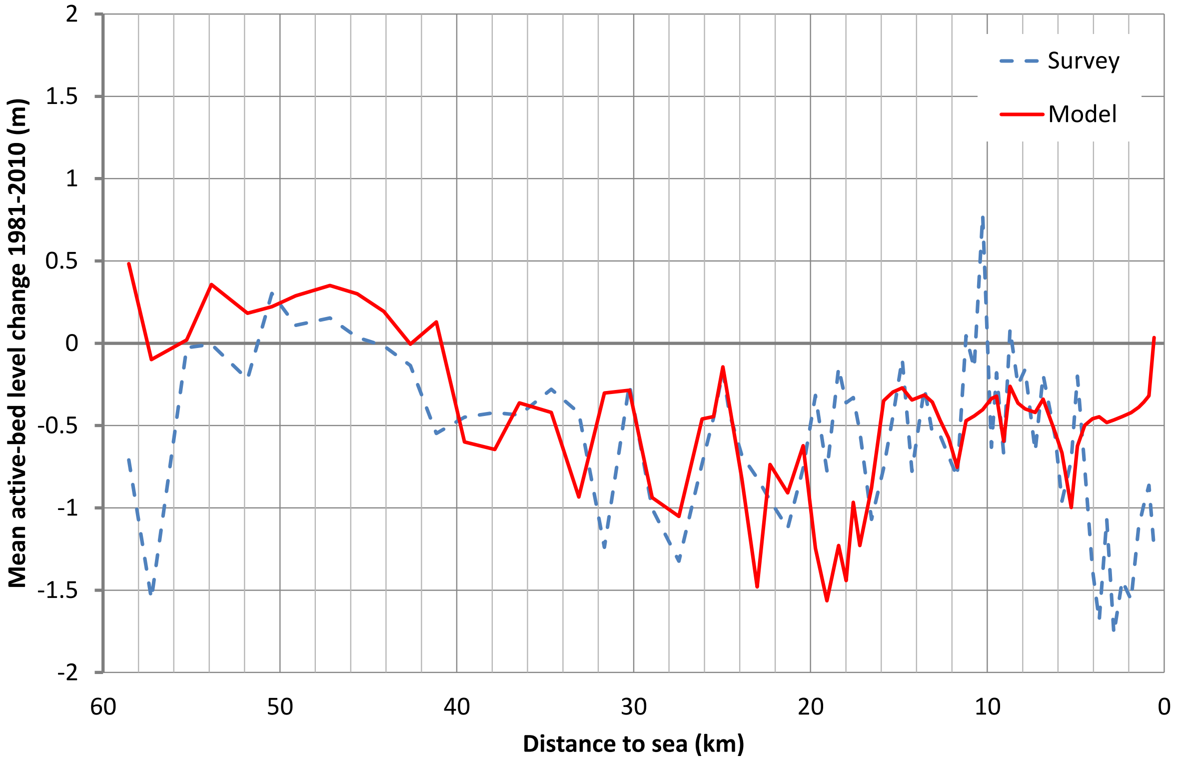


Figure 4-7: Modelled and surveyed bed level change 1981-2010.

After about 1981 (i.e. ignoring the first four years of model simulation) the bed level change predicted by the model closely matches the change measured by the cross-section surveys except for:

- The upstream most reach (upstream of about 55 km) where the surveys show much greater lowering of bed levels than predicted by the model. The reason that the upstream reach does not calibrate well is that it is very sensitive to the applied sediment feed. Bed levels in this reach move up and down to buffer the difference between the constant feed rate (and composition) applied at the upstream boundary with the varying transport rate within the model.
- Short areas within the extraction reaches (10-11 km and 17-20 km) have less degradation than predicted in the model. This difference is most likely caused by the under representation of transport rate in the model.
- The downstream most reach (downstream of about 4.5 km) where the surveys show a much greater lowering of the mean fairway bed level than the model. A closer inspection of the cross-sections in this reach shows that this lowering is mainly due to increasing width rather than changing bed elevation (see Figure 4-8). GRATE cannot represent the change in channel geometry so is not replicating this observed change.

The results of the first four years of the model simulation compare poorly against observed transport rates and bed level change. The reason for this is that during the first part of the model run the model rapidly adjusts bed level and composition to reach a more stable condition. In the case of the Ngaruroro model, the main changes experienced were: (1) the bed surface slightly coarsened during the initial part of the model run, reducing the transport rate slightly; and (2) local differences in transport rate between adjacent cross-sections were smoothed out through changing composition and elevation. Initial differences in transport rate between cross-sections occur because the model cross-sections have a fixed shape (a snapshot from when the 2010 survey was undertaken) which may be particularly susceptible to erosion or deposition. In reality most cross-sections experience a cyclic change as braids and bars migrate through the river.

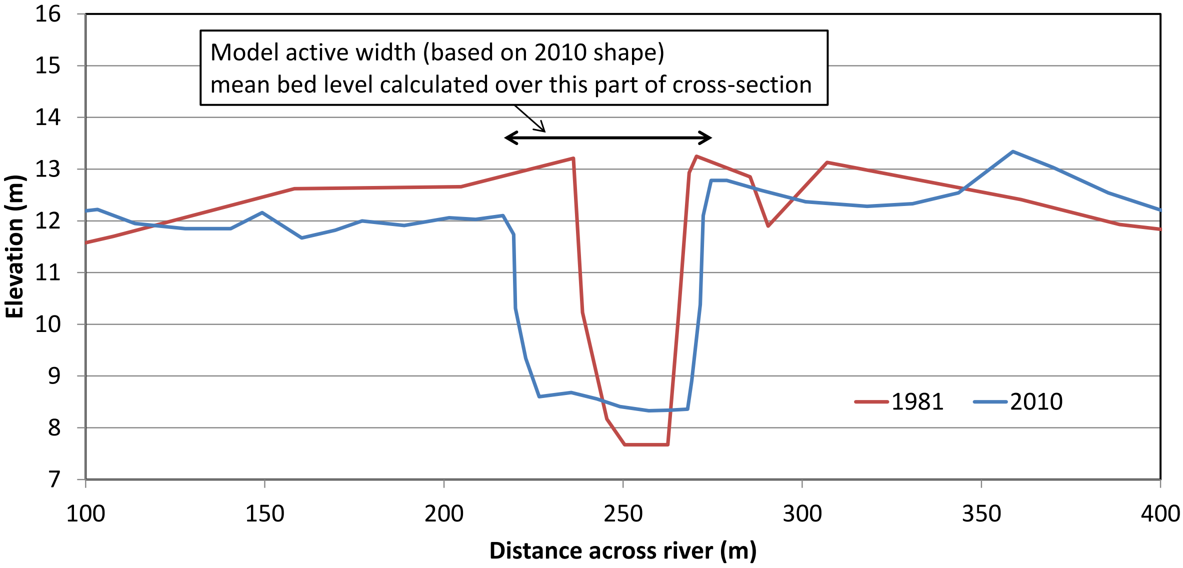


Figure 4-8: Channel widening experienced at cross-section 7 (2.8 km).

In summary, once the model has finished an initial ‘bedding in’ period, it replicates the patterns of transport rate and bed level change well. Although it represents the patterns well, the model underestimates transport rate by 30-40% compared to previous estimates and probably slightly overestimates surface grain size composition. Because the model reflects the patterns of transport and bed level change well it is a suitable tool for answering questions about the types of impact different changes will have on the river. However, the underestimation of transport rate means that the magnitude of gravel transport effects predicted by the model may need to be scaled up slightly.

The most likely causes of the difference between modelled and observed transport rate and sediment size include:

A. accuracy of transport formula in replicating fractional transport rates.

B. uncertainty over sediment feed composition and rate

C. uncertainty in sampled surface and subsurface size data

D. uncertainty in estimated transport rates.

A and B could be further investigated through sensitivity analysis using the model, and D could be reduced by updating the gravel balance analysis using recent survey data. A gravel balance performed using recent survey data is likely to have less uncertainty as bank positions are more constant since regular maintenance has been going on to stabilise them.

5 Scenario modelling

5.1 Scenario specification

Scenarios were developed and simulated in order to investigate the response of the river system to various outside drivers. All the scenarios simulated a 35 year period of morphological change. The initial bed levels for the scenario model were the most recent (2010) surveyed cross-sections as described in Section 3.1 (i.e. the initial mean fairway bed elevations were not adjusted to match an older historic level as they were for the morphological validation). The 1977 to 2012 flow and tide records used for the morphological validation were also used for the scenario modelling (with the exception of the climate change scenario which specifically investigates the impacts of changed flows and a higher mean sea level). This is based on the assumption that these time series were typical of the flows and tide levels which would be encountered in the future. This assumption is supported by the analysis of Griffiths and McKerchar [2012].

The scenarios, their purpose and specifications are described below.

1. **Historic extraction (Baseline)**

   Purpose: (1) This scenario provides information on the variations in gravel transport spatially along the length of the river, and temporally between years and as a result of individual flood events. (2) This scenario is used as a baseline for comparison against most of the other scenarios.

   Details: Historic extraction repeated as for the morphological validation simulation but starting from current rather than historic bed levels.

2. **No extraction**

   Purpose: (1) What are the effects on bed levels and flood risks if extraction were to cease? Which locations are most at risk? How rapidly would bed levels increase? How has extraction affected bed composition? How fast would gravel propagate further downstream toward the mouth? (2) This scenario provides a second baseline for testing Scenario 3 against.

   Details: This scenario is identical to the base case but has no gravel extraction for the entire simulation. Note that beach raking is included in this model. The effects of stopping beach raking are addressed separately in Scenario 6.

3. **Spatial and temporal impacts of specific gravel extractions**

   Purpose: Currently there is significant uncertainty over how the effects of individual extractions propagate upstream and downstream over different time scales. This is important when considering the effect of proposed extractions on specific locations of concern.

   Details: Several simulations of different localised extractions are compared against the no-extraction scenario. Scenarios involve 0.5 m deep 2 km long extractions simulated in different reaches from Fernhill to upstream of Maraekakaho (from cross-section 38 to 55). The extractions occur over a one year period once the model has bedded in.

Analysing bed level change relative to the no extraction scenario provides information about how the effects of specific extractions propagate in time and space.

4. **Localised ceasing of extractions**

   Purpose: Investigate the impacts on gravel transport and bed levels if extractions ceased in specific reaches.

   Details: Historic extractions are simulated everywhere except in the selected reaches where there is no extraction. Two different reaches are tested:

   i. no extraction from cross-section 47 downstream (downstream of Ohiti)

   ii. no extraction from cross-section 47 to 52 (from Ohiti to downstream of Maraekakaho).

5. **Extra extraction**

   Purpose: At some point in the future it may be desirable to undertake a large extra volume of extraction, e.g. exporting gravel to Auckland. This scenario investigates the consequences of that extraction.

   Details: An extra 300,000 m^3/year of extraction for 10 years is be simulated from cross-section 55 to 58 (34.66 to 39.56 km, upstream of Maraekakaho) on top of the historic extraction. Comparison of this scenario against the baseline scenario reveals the effects of the additional extraction.

6. **Effects of beach raking**

   Purpose: Gravel raking/ripping is undertaken in the Ngaruroro to remove vegetation and encourage gravel transport. It is expected that raking encourages gravel transport by: (1) mixing the surface layer with underlying material – this influences the surface composition by increasing the proportion of fine grains on the surface hence reducing armouring; (2) loosening the grains so there is less interlocking/imbrication, meaning that transport can occur at lower thresholds.

   Details: An experimental feature of GRATE has been developed to simulate the compositional mixing effects of raking (1), but the loosening effects (2) cannot be simulated. This scenario tests the significance of the compositional effects of raking by comparing simulations with and without raking. This scenario (as well as on-going research by the University of Auckland) helps address this uncertainty and enables improved understanding of the effects of raking and improved simulation of the effects of raking in morphological models.

7. **Changes in gravel supply**

   Purpose: What are the consequences of a large sediment pulse moving through the river system, for example as a result of a major landslide in the Ngaruroro headwaters?

   Details: Sediment inputs to the model are doubled and the composition of the sediment input is adjusted so that it is significantly finer (D_{50} of 12 mm, reduced from 19 mm in the baseline model).

8. **Climate change**

Purpose: What are the likely impacts of climate change on gravel transport in the Ngaruroro? How could the current extraction regime be influenced by climate change?

i. Sea Level Rise

Details: Sea levels are increased by 0.8 m for the whole duration of the model run. By applying the change at the start of the simulation then keeping it constant it is easier to separate out the effects of the change than simulating a gradual change. Sea level rise was included by raising water levels at the downstream tidal boundary. A sea level rise of 0.8 m by 2010 is the conservative MFE (2008a) guidance value.

ii. Decreased River Flows

Details: Flows are decreased by 5% for the whole hydrograph throughout the duration of the model. A 5% decrease was selected based on the MFE (2008b) 2.5% to 5% reduction in annual rainfall for the Ngaruroro catchment by 2090 relative to 1990. This is a simplified assumption, and more detailed analysis of the effects of climate change on different aspects of the flow distribution table would be required to inform modelling of the full effects of climate change on gravel transport.

5.2 Results

5.2.1 Baseline

The modelled annual bedload transport rate and inter-annual variability in transport rate at Ohiti and Fernhill is shown in Figure 5-1 and Figure 5-2 respectively. The transport past Ohiti is important as this represents the gravel supply into the main depositional reach. Fernhill has a lower average transport rate as it is approximately half way along the depositional reach. The model shows large variability in transport rate between different years, particularly at Ohiti. The annual variability in transport rate is predominantly influenced by the flows experienced during the year.

It is notable that during moderate to high transport years transport at Fernhill is only 50-60% of that at Ohiti, whereas during low transport years Fernhill transport rates are very similar to those at Ohiti. This shows that during low transport years there is little deposition between these locations. The reason for the difference in the way the Ohiti and Fernhill transport rates behave during high and low transport years is that transport past Ohiti is much more flood/fresh dominated whereas a higher proportion of the total transport occurs during periods of more moderate flow at Fernhill. An example of the difference in the way the two locations respond to flows can be seen in Figure 5-3.

As well as investigating the temporal variability in sediment transport the baseline model was used to investigate the future propagation of gravel into the coastal reach. At the start of the scenario simulation, gravel was assumed to dominate the bed surface composition down to 3.3 km from the coast (between cross-sections eight and nine) beyond which the bed was primarily composed of sand. The initial and final D_{50} profiles after 35 years of simulation are shown in Figure 5-4. The model composition in this reach fluctuates significantly with time

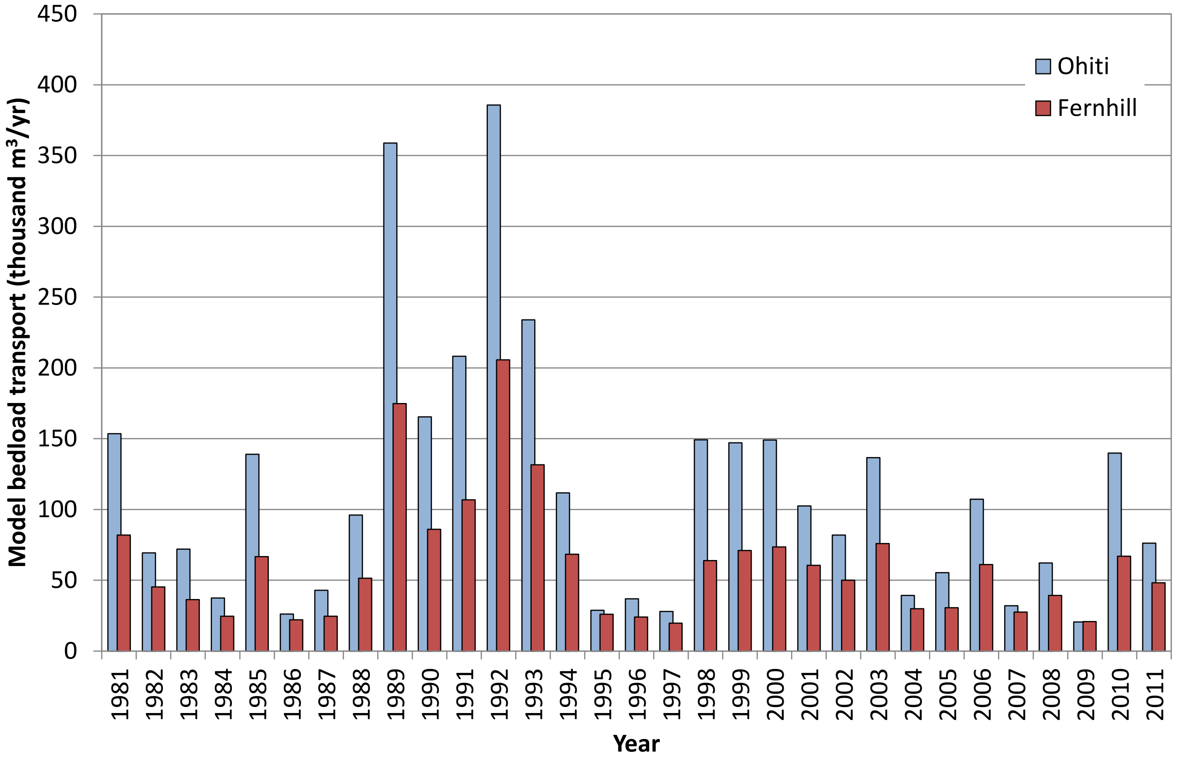


Figure 5-1: Modelled annual bedload transport rate at Ohiti and Fernhill.

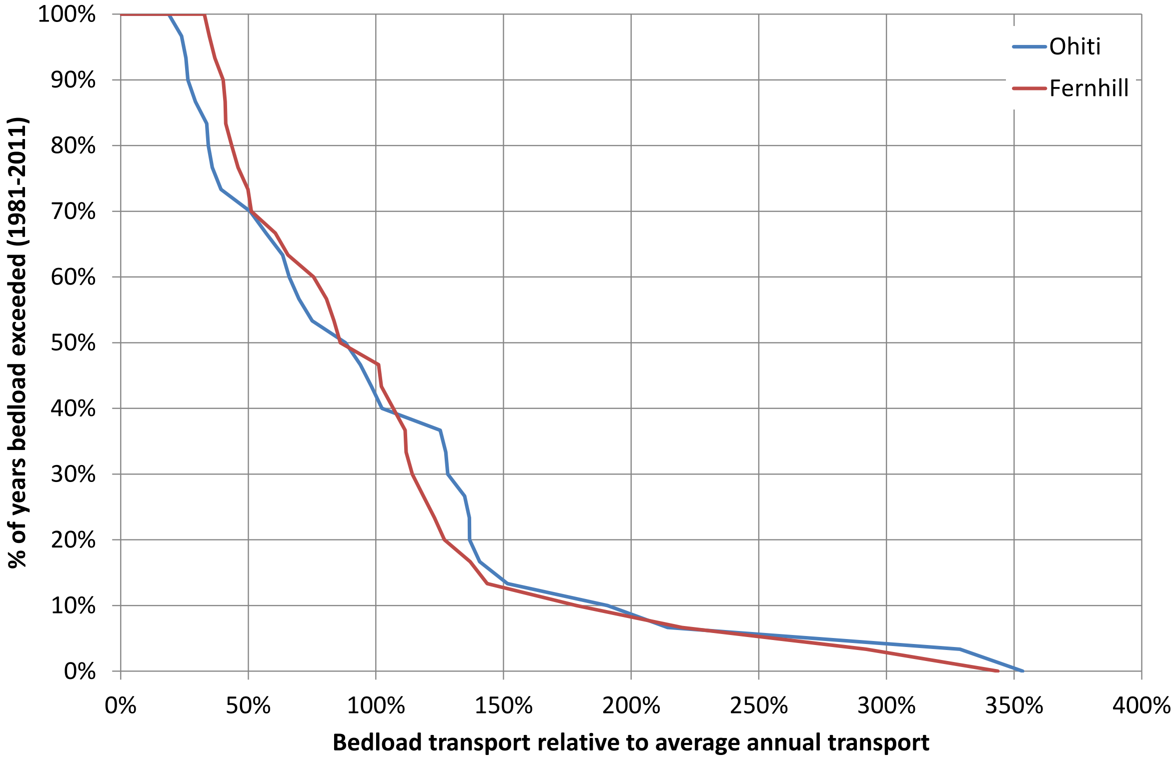


Figure 5-2: Inter-annual variability in transport rate at Ohiti and Fernhill.

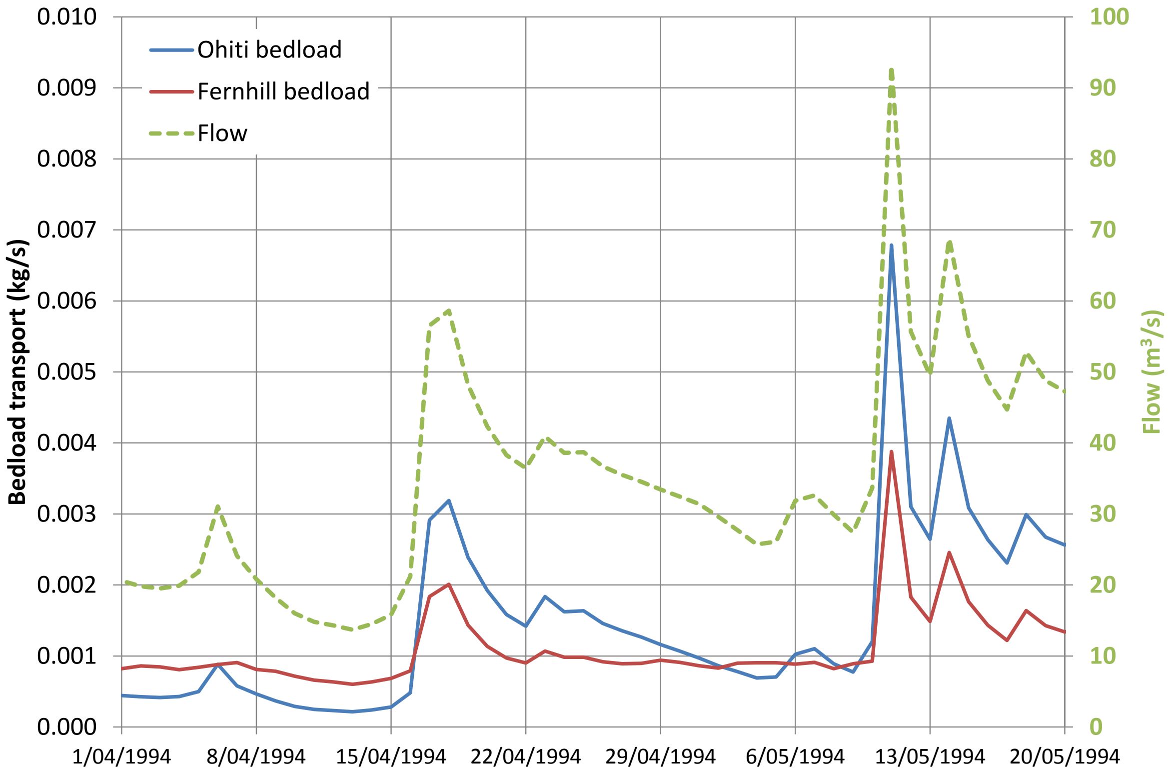


Figure 5-3: Time series of flow and transport rate at Ohiti and Fernhill for April 1994.

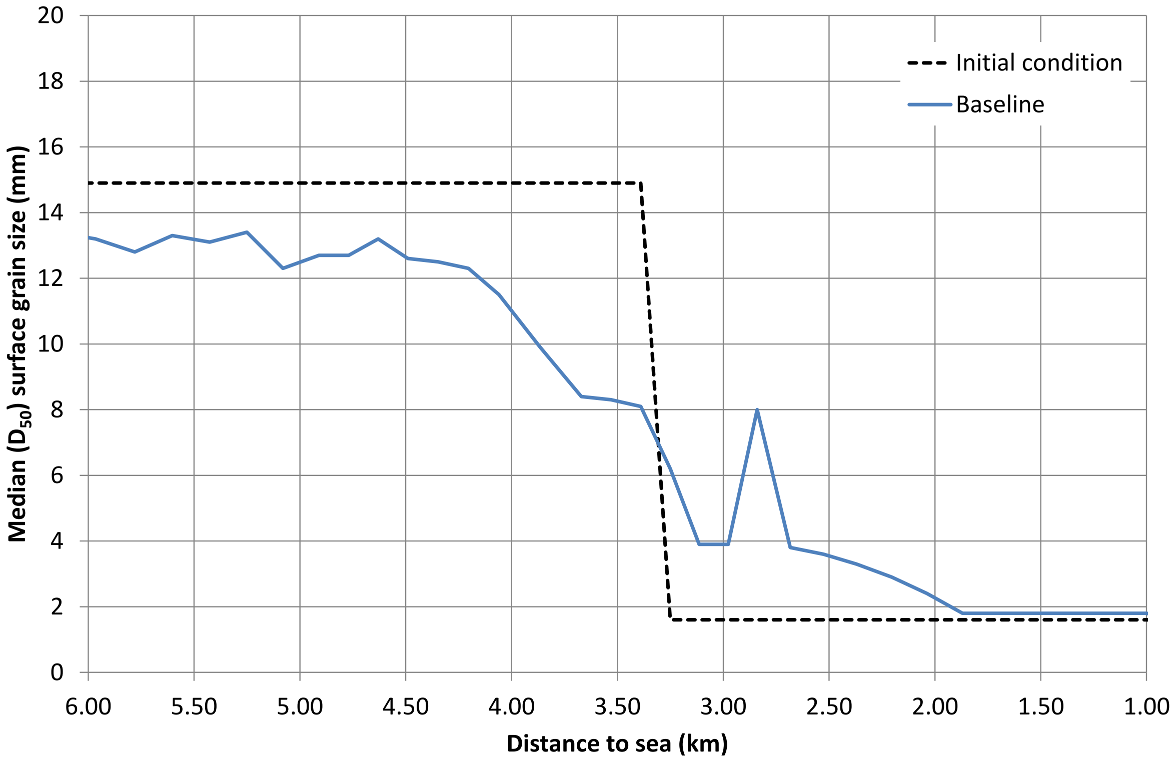


Figure 5-4: Modelled propagation of gravel into the coastal reach.

during the simulation and is influenced by the fact that the subsurface composition is fixed. For these reasons the confidence that can be placed in the model results is limited. However, some conclusions can be drawn from the results. The model shows that no gravel propagates closer than 1.9 km to the sea and there is little gravel transported past 3.3 km.

5.2.2 No Extraction

By comparing the no-extraction and baseline scenarios we are able to investigate the impacts of extraction. Figure 5-5 indicates that bed levels would currently be up to 2.3 m higher around Fernhill if no extraction had taken place and approximately 1 m higher on average for the whole reach from Maraekakaho to Chesterhope. These differences are a combination of gravel deposited by the river not being removed by extraction and degradation below 1977 bed levels caused by extraction.

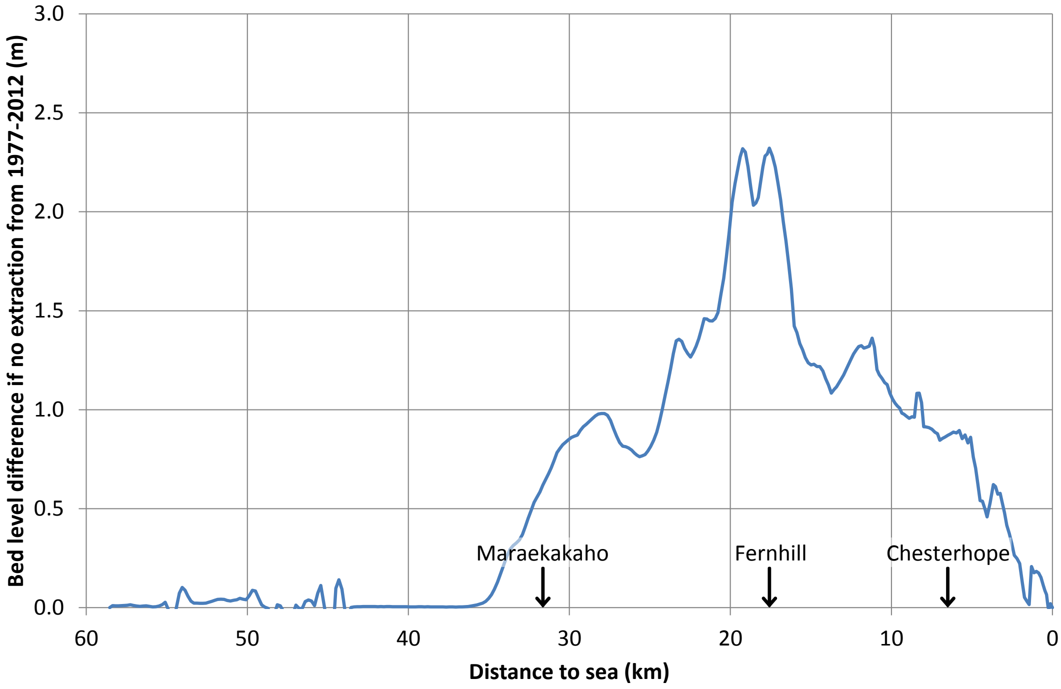


Figure 5-5: Bed level effects if no historic extraction had taken place from 1977 to 2012.

Analysis of the bed level change predicted in the no-extraction scenario provides information about the natural rate of bed aggradation without extraction (see Figure 5-6). This analysis shows there is little natural aggradation upstream of Ohiti, with aggradation rates peaking at approximately 30 mm/year around Fernhill. This confirms the gravel balance analysis by Gary Williams [1997] which concluded that extraction above Ohiti should be restricted to the removal of accumulated reserves as there was little deposition in this reach.

The effects of extraction on bedload transport rate are shown in Figure 5-7. The model shows that extraction has had relatively little effect on bedload transport rate although it has slightly increased transport from Maraekakaho to Fernhill and decreased it downstream of Fernhill. The likely reasons for this change are that the extraction has resulted in a slight steepening of the bed gradient upstream of Fernhill and flattening downstream. These changes don’t affect the total gravel supply but they change the distribution of gravel deposition, focussing deposition around Fernhill where the highest rates of gravel extraction have occurred historically.

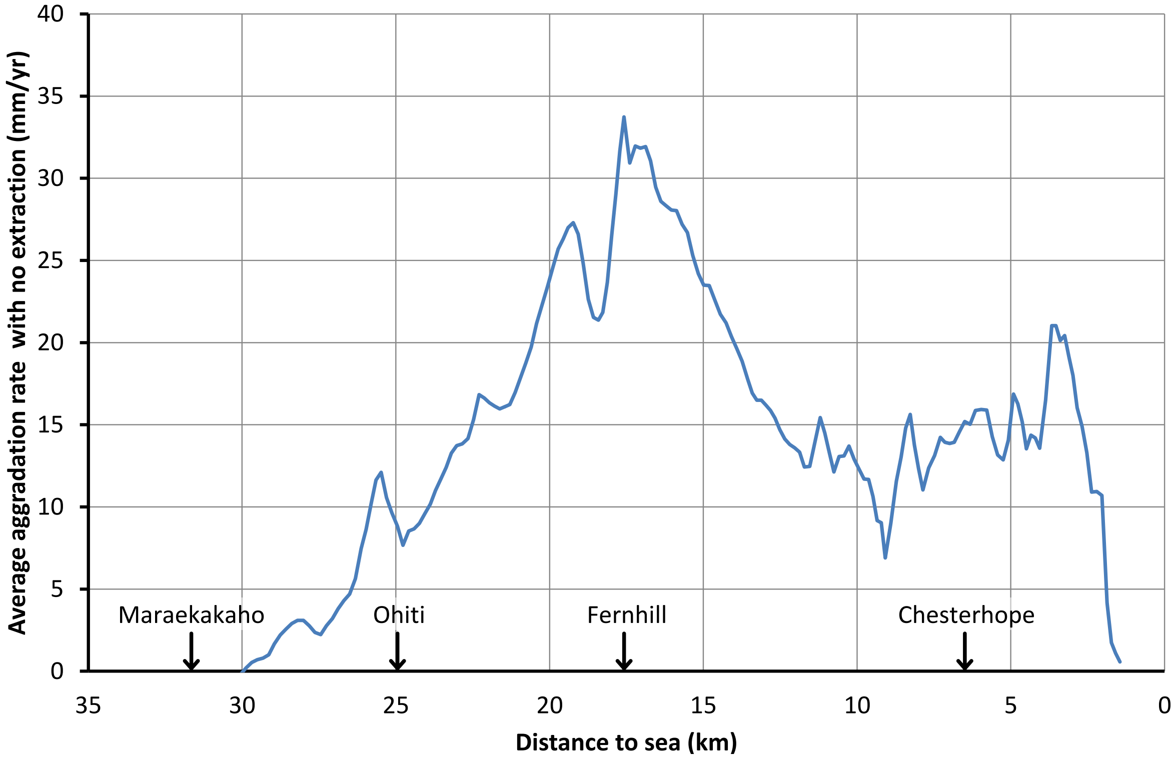


Figure 5-6: Natural aggradation rates for the no-extraction scenario.

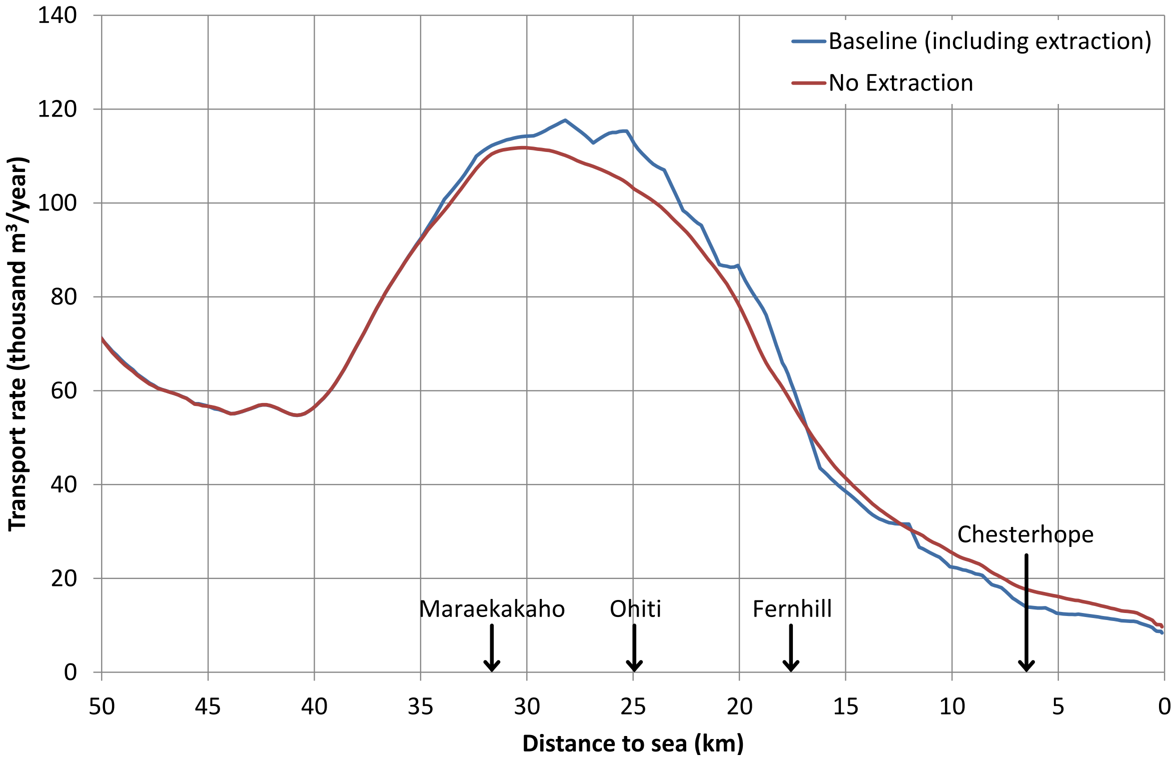


Figure 5-7: Effects of extraction on average bedload transport rate. The baseline transport rate differs from Figure 4-3 because it is averaged over the full duration of the model run (rather than the 1985 to 1993 period only).

The effects of gravel extraction on the propagation of gravel downstream into the coastal reach were investigated by comparing the bed composition of the baseline and no-extraction scenarios at the end of the 35 year simulation (see Figure 5-8). The model shows that extraction reduced the amount of gravel propagating downstream but that even with no gravel extraction there is no gravel transport within 1.8 km of the sea. For significant amounts of gravel to reach the coast, it is likely that major aggradation of the bed would first have to occur in order to increase the slope of the downstream reach.

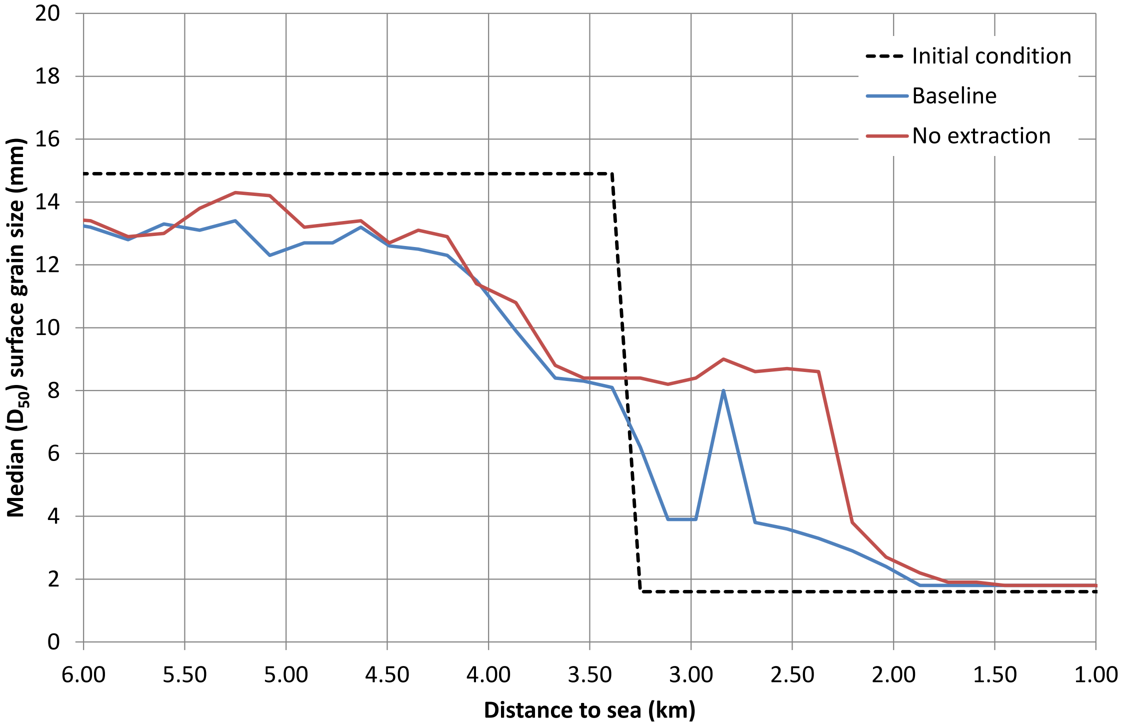


Figure 5-8: Modelled propagation of gravel into the coastal reach with and without extraction.

5.2.3 Spatial and temporal impacts of specific gravel extractions

Over time, the effects of a specific extraction on bed levels can advect and diffuse both upstream and downstream. To investigate the time scale and magnitude of these effects several scenarios of different short duration localised extractions were simulated. By comparing these scenarios against the no-extraction scenario it is possible to separate out the impacts of the specific scenarios on bed levels and gravel transport rates.

Figure 5-9 shows the propagation of extraction impacts on bed levels for 1, 5, 10 and 20 years after extraction has ceased. The simulated extractions occurred in 1987 and in all cases 0.5 m depth of gravel was removed over a 2 km reach. Three extraction locations, covering the reach with the highest demand for extraction (from Fernhill to Maraekakaho), were simulated. The volume of gravel extracted in each location was in the range 310,000 to 330,000 m^3.

The results of the scenario show that the extraction holes diffuse over an approximately 10 km long section of river and that the low-point of the extraction hole advects slowly upstream. It is notable that the majority of the change occurs between one and five years after the extraction. Inspection of the annual variability in bedload transport (Figure 5-1) reveals that 1988 and 1999, 2-3 years after the extraction, were high transport years. This shows that the rate at which an extraction affects the adjacent reaches upstream and downstream is highly dependent on the amount of transport taking place.

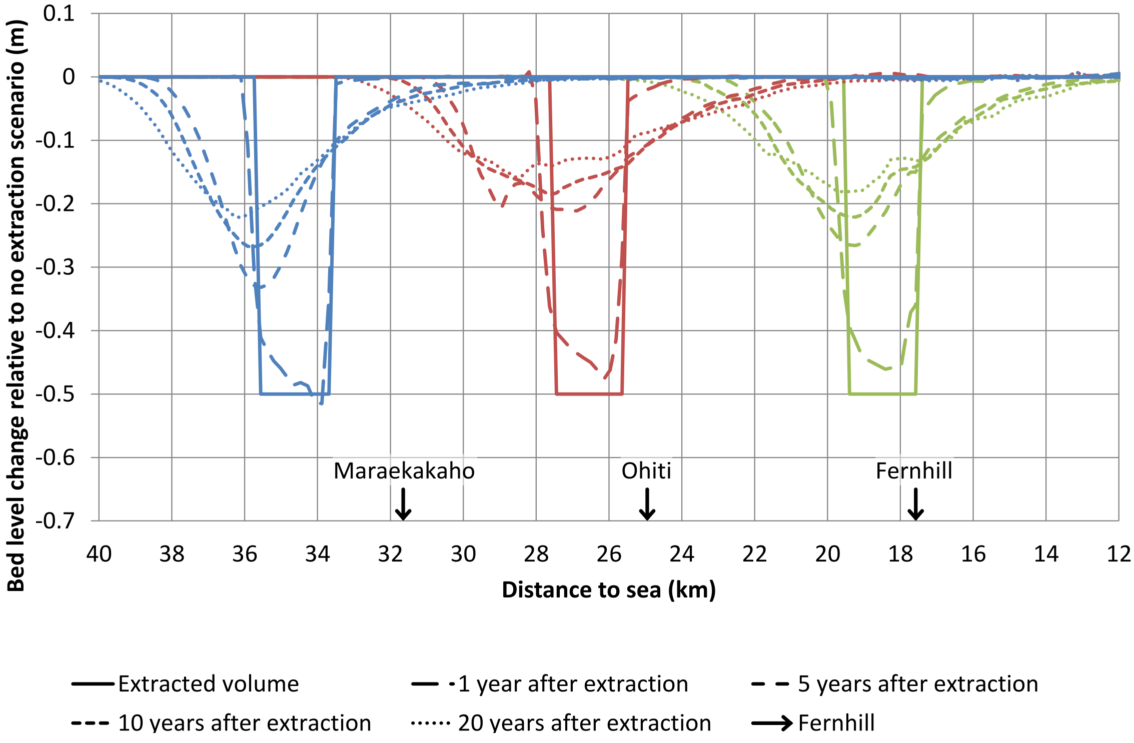


Figure 5-9: Advection and diffusion of 2 km long 0.5 m deep extraction holes.

5.2.4 Localised ceasing of extraction

This scenario investigated the consequences of ceasing extraction in two reaches: downstream of Ohiti and from Maraekakaho to Ohiti. Figure 5-10 shows the effects on bed levels if no historic extraction had occurred in these reaches. Extraction downstream of Ohiti has a much bigger impact as more extraction has occurred historically in this reach.

It is notable that extraction downstream of Ohiti has impacted bed levels as far upstream as Maraekakaho. Given that the majority of natural deposition occurs downstream of Ohiti (see Figure 5-6) it is likely that bed levels in the Maraekakaho to Ohiti reach could be controlled by extraction downstream of Ohiti if it was necessary to cease extraction in the Maraekakaho to Ohiti reach. The opposite is not true, however, if extraction ceased downstream of Ohiti. In that case it would not be possible to control aggradation solely through extraction upstream. The impacts of extractions upstream of Ohiti don’t extend as far as Fernhill, where the highest rates of natural aggradation occur.

5.2.5 Extra extraction

This scenario simulated additional extraction upstream of Maraekakaho. The effects on bed levels of 300,000 m^3/year additional extraction for 10 years are shown in Figure 5-11.

The simulation results show that the extraction initially lowers bed levels by over 1.5 m and that the extraction hole only fills slowly once extraction ceases. The diffusion of this large scale extraction is very similar to the diffusion of the smaller extractions investigated in Scenario 4 except the reduction in depth of the extraction hole is slower because of its larger size.

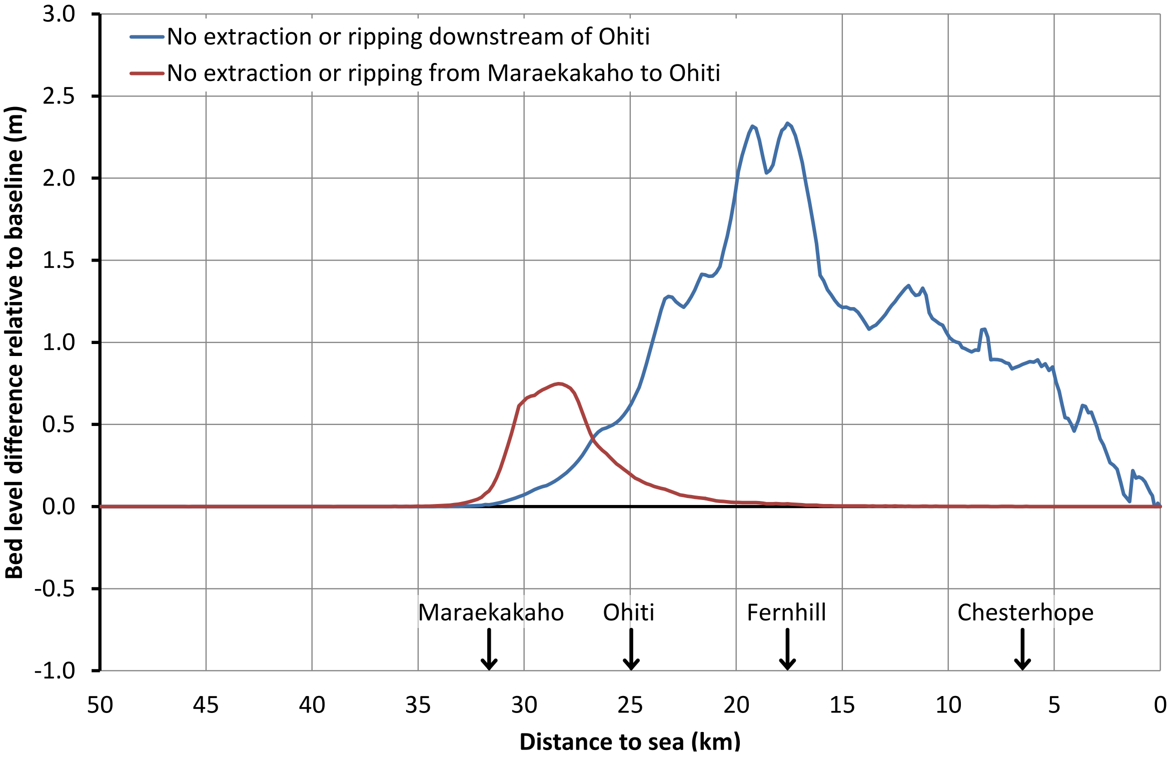


Figure 5-10: Bed level effects of ceasing extraction in different reaches. The bed level changes are relative to the bed levels from the baseline scenario.

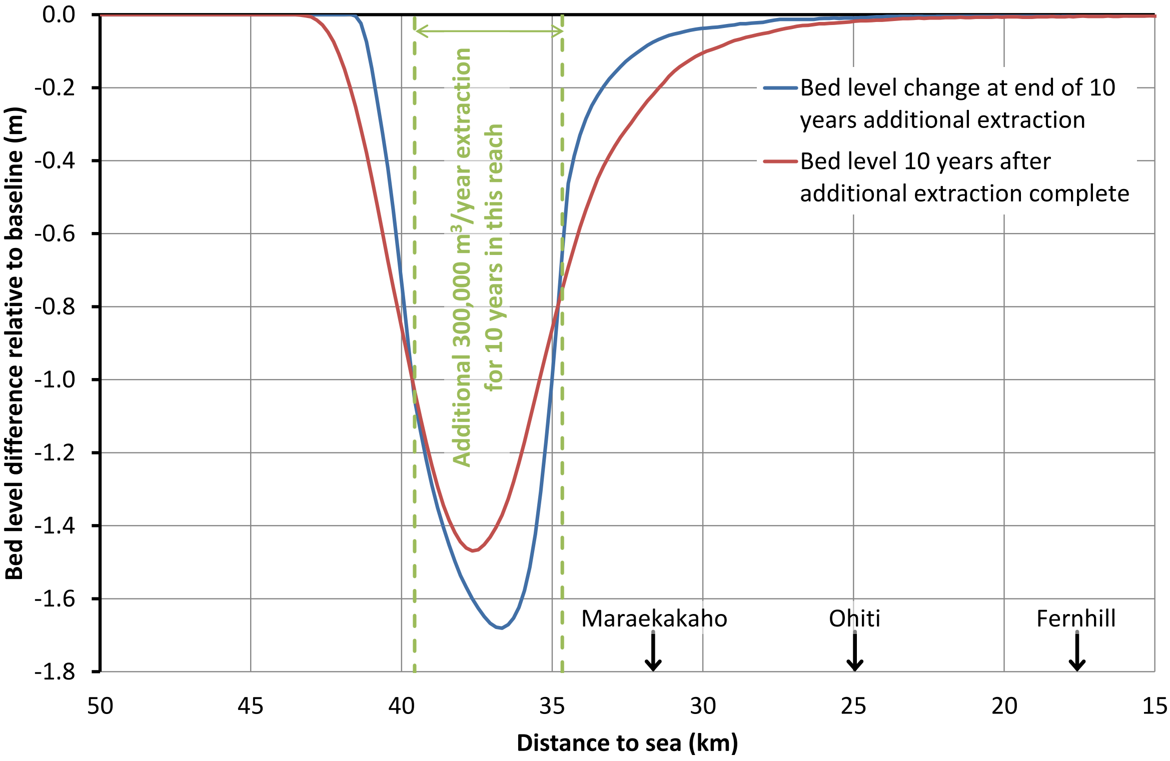


Figure 5-11: Bed level effects of additional extraction upstream of Maraekakaho. The bed level changes are relative to the bed levels from the baseline scenario.

5.2.6 Beach raking

By running simulations with and without beach raking it is possible to separate out the effects of the raking from the other drivers of change such as natural deposition and extraction. It should be remembered that the model implementation of raking assumes complete mixing of the surface and subsurface to the depth of the raking but does not represent the loosening effects of raking. Figure 5-12 shows the effects of beach raking on modelled transport rate.

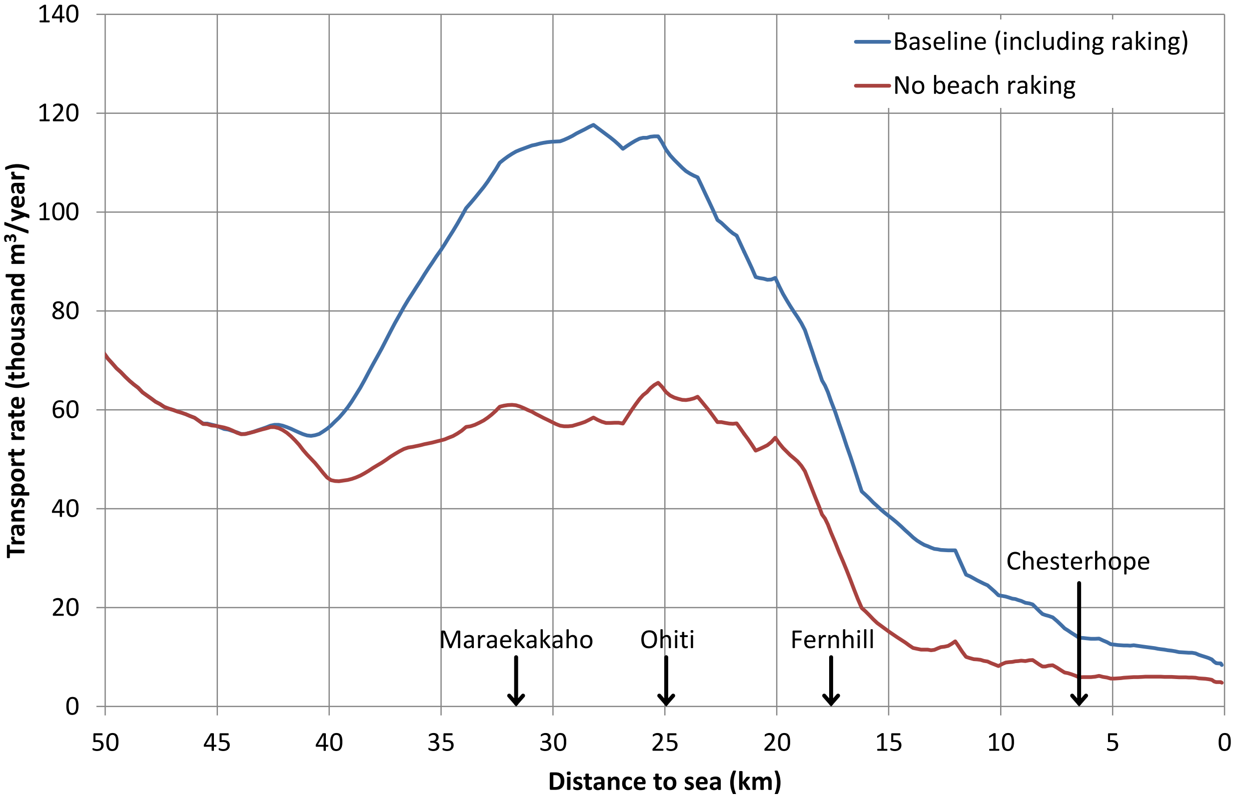


Figure 5-12: **Effects of raking on modelled mean annual transport rates.**

The results clearly show that beach raking has increased model transport rates by up to 100%. However the effects on transport rate could be less if the mixing of bed surface and substrate is less thorough in reality than assumed in the model. Despite this uncertainty, the model results do suggest strongly that raking can have a significant influence on transport rates. This supports anecdotal observations of Hawkes Bay Regional Council staff that raking is effective for mobilising armoured islands and bars.

Figure 5-13 shows the difference in bed levels at the end of the 35 year simulation between scenarios with and without raking. The results show that by increasing transport rates, beach raking has resulted in lower bed levels in the raked reaches and increased bed levels downstream of them.

5.2.7 Changes in gravel supply

The bed level effects of reducing the grain size of the upstream sediment supply and doubling the supply rate is shown in Figure 5-14.

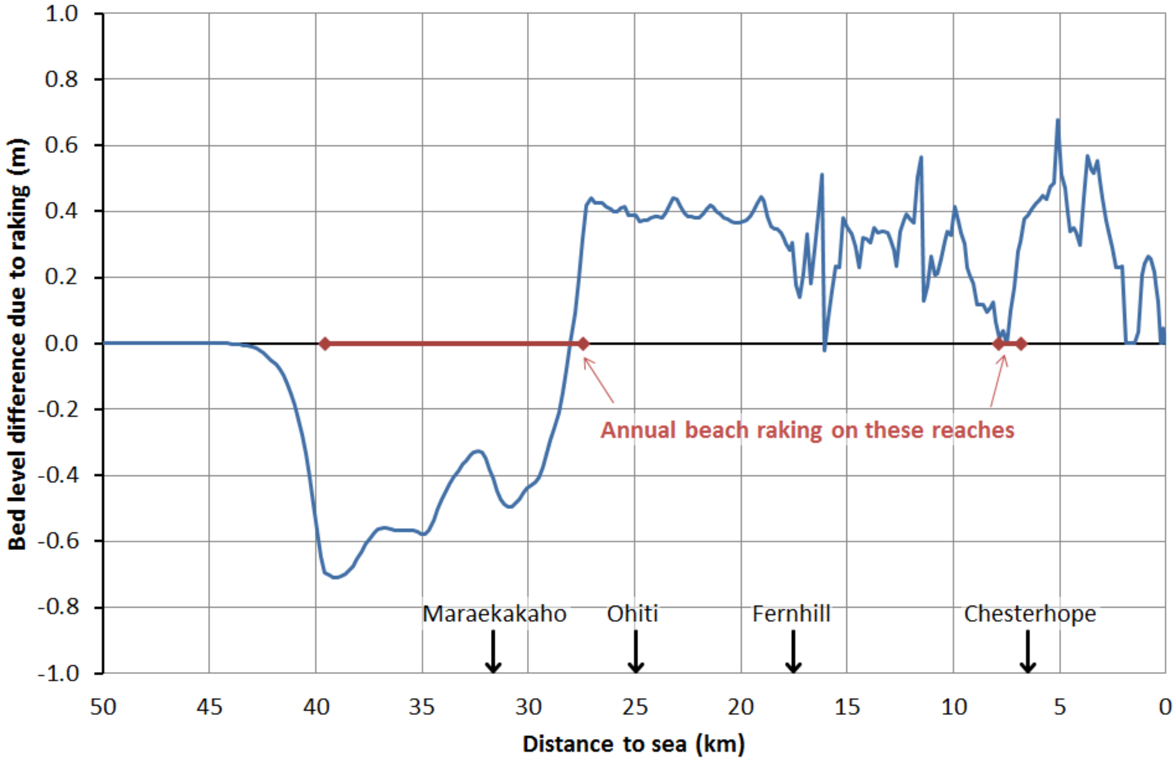


Figure 5-13: **Effects of 35 years of beach raking on bed levels.** The bed level differences are relative to the bed levels from the baseline scenario.

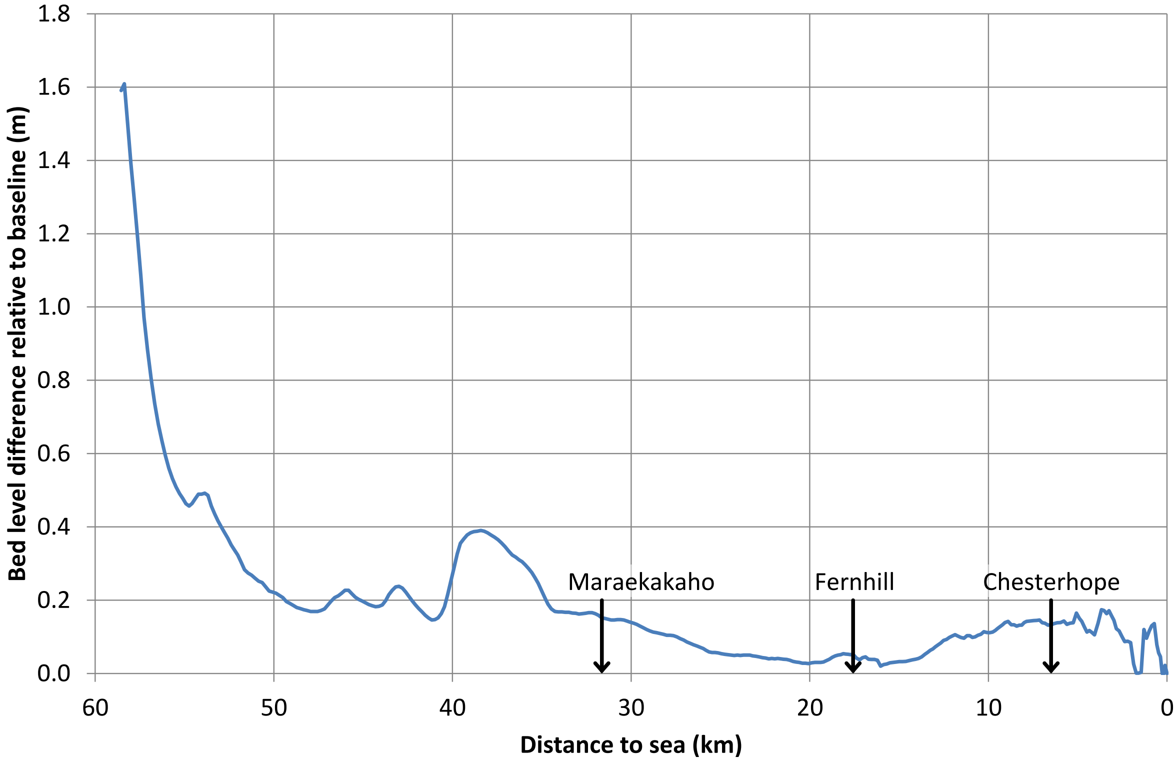


Figure 5-14: **Effects of increased sediment supply on bed levels.** The bed level changes are relative to the bed levels from the baseline scenario.

The scenario results show that the downstream bed level effects of a major increase in sediment supply are relatively small. After 35 years of increased feed bed levels are only predicted to increase up to 0.2 m in the lower, stopbanked reaches of the river. The large bed level increases at the upstream end of the model only propagate downstream slowly (~5 km in 35 years) due to the large amount of storage in the channel.

5.2.8 Climate change

Two climate change scenarios investigated the sensitivity of gravel transport to a 0.8 m increase in sea level and a 5% reduction in river flow, respectively. The effects of these two scenarios on bed levels and transport rates are shown in Figure 5-15 and Figure 5-16 respectively.

A 5% reduction in flow causes a 6-10% reduction in bedload supply to the extraction reaches. The main effect of this is a reduction in the gravel deposition rate downstream of Ohiti, causing a slight lowering of bed levels compared to current conditions.

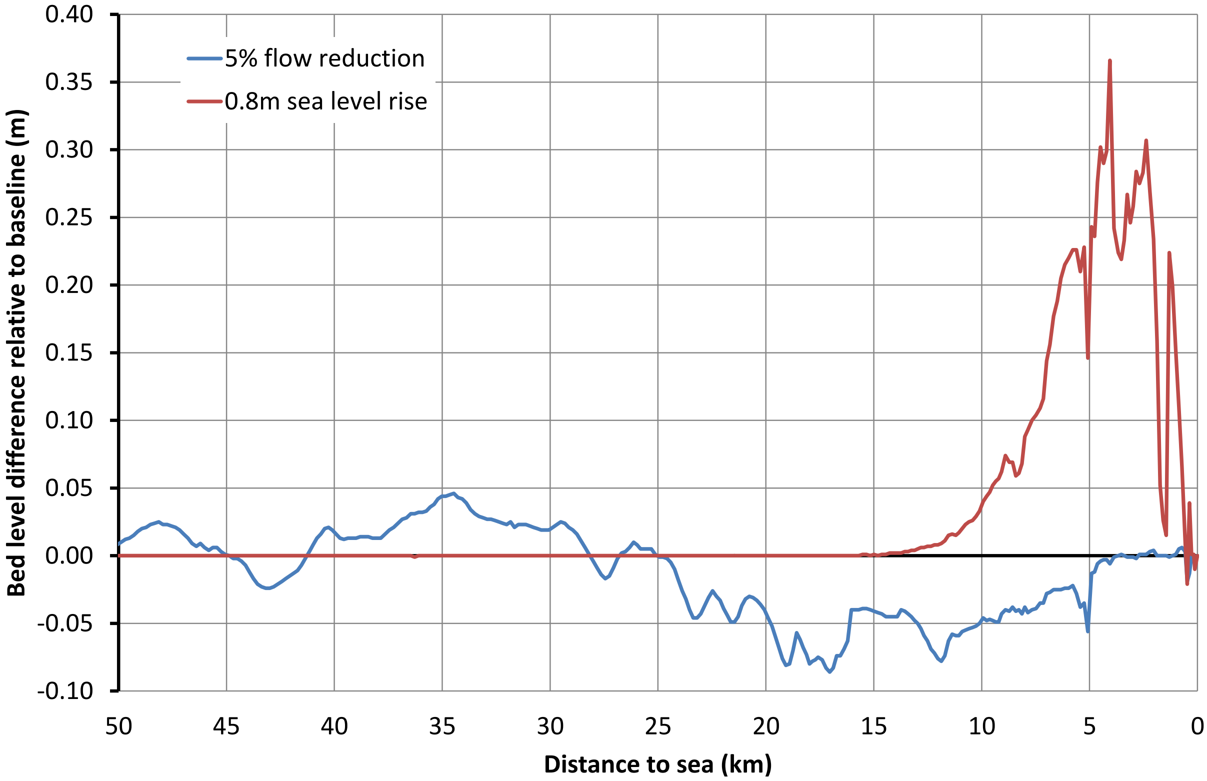


Figure 5-15: Effects of climate change on bed levels. The bed level changes are relative to the bed levels from the baseline scenario.

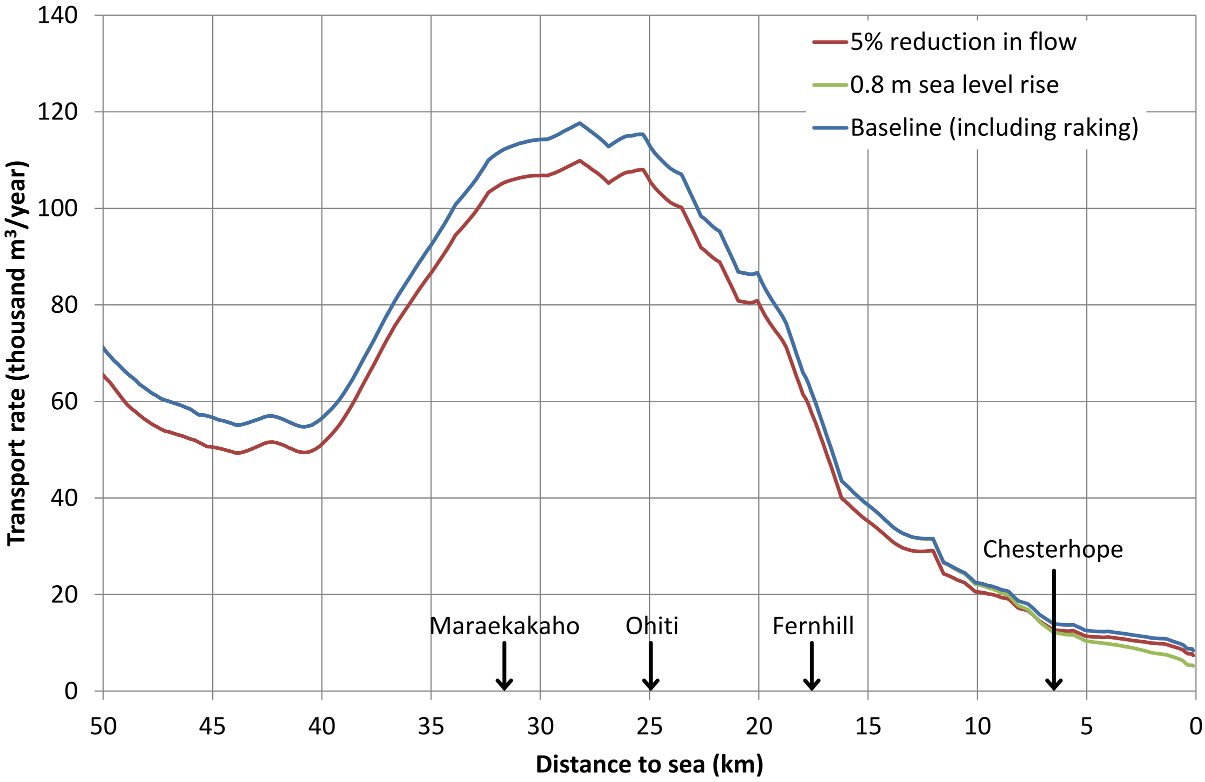


Figure 5-16: **Effects of climate change on bedload transport rates.**

A 0.8 m increase in sea level increases water levels and reduces velocities in the coastal reach of the river. This backwater effect is greatest at the mouth of the river, with reducing effect upstream to about 15 km where there is no significant impact. The reduced velocities cause bed aggradation as a result of reduced transport capacity. The majority of the additional aggradation caused by sea level rise in the lower part of the river is sand rather than gravel. This happens because the reduced velocities in the downstream most reach prevent gravel being transported as far, shifting the gravel-sand transition upstream. Some of the sand that would previously have been transported to the coast is deposited in the downstream part of the river, raising bed levels and also reducing coastal sand delivery.

6 Conclusions

The model hydraulics were calibrated to peak flood levels surveyed after two flood events. Over 90% of surveyed levels were within 1 m of the modelled average water level and 75% were within 0.5 m. Given the spread in surveyed water levels and the uncertainties in cross-section shape and level at the time of the flood, this represents a reasonable calibration.

Morphological calibration was undertaken for the period 1977 to 2012. During calibration the abrasion rate was increased and beach raking was included in the model in order to improve model fit. This suggests that beach raking and abrasion both have significant influence on gravel transport processes in the Ngaruroro. Following these adjustments, the model reproduced well the observed bed-level change and the propagation of the gravel tongue. Model calculations of surface grain size distribution were slightly coarser than observed. The most significant differences between model results and observed river processes was that the model-predicted bedload transport rates were approximately 30-40% less than previous estimates of transport rate based on budgeting calculations. Despite this difference, the model did reproduce the shape of spatial changes in transport rate well.

Key results of the scenario modelling are:

1. Gravel transport in the Ngaruroro is highly variable year to year, depending on the river flows. Annual gravel transport past Ohiti into the main deposition reach varied from less than one third to over three times the mean annual load in the 35 years of simulation.

2. There is significantly more inter-annual variability in the amount of gravel transported past Ohiti than past Fernhill. The reason for this is that gravel transport through sections with constrained width (such as Ohiti) is more influenced by floods.

3. Natural aggradation is occurring from Ohiti down to the limit of the gravel. The fastest aggradation is occurring around Fernhill and averages more than 30 mm/year. Little natural aggradation occurs upstream of Ohiti, indicating that once the available gravel has been extracted, little or no further extraction will be sustainable in this reach.

4. The model shows that in the coastal reach some gravel does propagate downstream of 3 km from the sea but this is very variable over time and none propagates beyond 1.9 km from the sea. However, there is considerable uncertainty in the modelling of the propagation of gravel into the coastal reach due to the fixed subsurface composition in the model.

5. If no extraction had taken place since 1977, bed levels would currently be up to 2.3 m higher around Fernhill and approximately 1 m higher on average for the whole reach from Maraekakaho to Chesterhope. Without extraction, flood capacity would be significantly lower than it is currently.

6. Historic gravel extraction has not affected the total gravel supply rate into the extraction reaches, but it has slightly changed the distribution of gravel

deposition, focussing deposition around Fernhill where the highest rates of gravel extraction have occurred historically.

7. Gravel extraction does reduce the propagation of gravel into the coastal reach. However, even with no extraction, no gravel propagates closer than 1.8 km from the sea. For significant amounts of gravel to reach the coast it is likely that major aggradation of the bed would first have to occur in order to increase the slope of the coastal reach.
8. Individual extractions influence bed levels within approximately 5 km upstream and downstream of the limits of the extraction. The rate at which the bed level effects diffuse is highly dependent on the transport rate (i.e. in high transport years extraction holes diffuse quickly and in low transport years slowly).
9. It would be possible to control aggradation between Maraekakaho and Ohiti with downstream extraction if extraction in this reach had to cease. It would not, however, be possible to control bed levels downstream of Ohiti using upstream extraction as the effects of upstream extraction do not propagate far enough.
10. Beach raking has a significant impact on transport rate, increasing transport in and downstream of raked reaches by reducing surface armouring. Beach raking causes degradation (or reduced aggradation) of raked reaches and increased deposition downstream.
11. A 5% reduction in flow (assumed to occur as a result of climate change) was found to cause a 6-10% reduction in gravel supply. The true effect of climate change is likely to be more complex as different parts of the flow regime (floods, low flows, etc.) may be affected in different ways.
12. A 0.8 m sea level rise causes a reduction in transport rate at the downstream end of the river with associated aggradation of the bed and reduction in sand supply to the coast. This sea level rise influenced bed levels up to 15 km from the coast.

Morphological modelling generally has a high amount of uncertainty associated with it, but through careful use of historic data to calibrate/validate the model this study demonstrates the confidence that can be placed in the model results. Overall, the morphological modelling has performed well, replicating historic river conditions and providing insight into the gravel transport processes in the Ngaruroro River.

7 Recommendations

The Ngaruroro morphological model was developed to (1) inform gravel management on the Ngaruroro River and (2) to serve as a pilot study for further analysis on other rivers such as the Tukituki. No recommendations are given regarding (1) as gravel management decisions need to be informed by other considerations in addition to the conclusions from this study. These other factors will be addressed by the wider review of riverbed gravel management and include future gravel demand, ecological effects, economic considerations, and currently available gravel supplies [Tonkin and Taylor, 2010]. Recommendations are given below regarding (2).

1. Prior to undertaking morphological calibration the gravel balance analysis should be updated with the latest survey data. When updating the gravel balance analysis, inclusion of abrasion effects should be trialled in order to test their significance on the calculated transport rates.

2. Due to the large inter-annual variability in transport rates between years, as long a period of flow data as is available should be used for scenario modelling. In hindsight, this study would have benefitted from using a longer flow series for the scenario modelling.

3. Records of beach raking should be kept in order to allow accurate inclusion in future analysis (i.e. reaches and rough % width raked each week).

4. Field investigations into the compositional mixing effect of beach raking (by taking Wolman and sub-surface samples before and after raking) should be undertaken to inform the inclusion of this process in the model.

5. Field/laboratory investigations into the loosening effect of raking on gravel mobility should be undertaken to better understand their importance.

6. 2D modelling of beach raking should be undertaken in order to understand the cross-section shape effects of annual raking. 1D modelling cannot investigate the effects of cross-section shape change but this can have an effect on transport rate.

8 Acknowledgements

This study would not have been possible without the help of Jeremy Walsh developing and improving the GRATE software and Murray Hicks providing advice on the key modelling decisions. The support of Hawkes Bay Regional Council Staff was also invaluable including: Gary Clode for his support and enthusiasm for the project; grain size data collection undertaken by Graham Edmondson, Neil Daykin and Dean Foote; previous Mike-11 modelling work undertaken by Craig Goodier; and data supply regarding extraction and beach raking from Vincent Byrne and Darren Gorst.

9 References

Adams, J. (1978). Data for New Zealand pebble abrasion studies. *New Zealand Journal of Science 21*: 607-610.

Gaeuman, D.; Andrews, E.D.; Krause, A.; Smith, W. (2009). Predicting fractional bed load transport rates: Application of the Wilcock-Crowe equations to a regulated gravel bed river. *Water Resources Research 45(6)*: 1-15.

Garcia, M.H. (2008). Sediment Transport and Morphodynamics. *In:* Garcia, M.H. (ed.). ASCE Manuals and Reports on Engineering Practice No. 110: Sedimentation Engineering Processes, Measurements, Modelling and Practice, pp. 21-163. American Society of Civil Engineers, Virgina.

Griffiths, G.; McKerchar, A. (2012). Temporal variation in rainfall, flood occurrence and bedlevel in the Hawkes Bay Region. *NIWA Client Report No CHC2012-020*.

Hicks, M.; Measures, R.; Hoyle, J.; McKerchar, A.; Griffiths, G.; Bind, J. (2011). North Bank Hydro Project – Geomorphology, sedimentation, and flood hydrology investigations. *NIWA Client Report No CHC2011-078*.

Marshall, P. (1927). The wearing of beach gravels. *Transactions of the Royal Society of New Zealand 58*: 507–532.

McBryde D.J. (1989). Heretaunga Plains Gravel Resource Management Plan. *Hawkes Bay Catchment Board, Napier*.

Measures, R. (2012). Modelling gravel transport, extraction and bed level change on the Waimakariri River. *NIWA Client Report No CHC2012-092*.

Measures, R.; Hicks, M. (2011). Gravel Supply and Transport Scoping Report. *NIWA Client Report No CHC2011-143*.

Ministry for the Environment. (2008a). Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand. 2nd edition. Revised by Ramsay, D, and Bell, R. (NIWA). Prepared for Ministry for the Environment. Viii+127 p.

Ministry for the Environment. (2008b). Preparing for climate change. A guide for local government in New Zealand. *Ministry for the Environment Publication No. 891, Wellington, (July)*. Iii+38 p.

NIWA (2012A) WRENZ Water Resources Explorer New Zealand. http://wrenz.niwa.co.nz.

NIWA (2012B). NIWA Tide Forecaster. http://www.niwa.co.nz/services/online-services/tide-forecaster.

Parker, G. (1991A). Selective sorting and abrasion of river gravel. I: Theory. *Journal of Hydraulic Engineering 117(2)*: 131-149.

Parker, G. (1991B). Selective sorting and abrasion of river gravel. II: Applications. *Journal of Hydraulic Engineering 117(2)*: 150-171.

Tonkin & Taylor (2010). Scoping Report: Review of Riverbed Gravel Management. *T&T Ref: 85047*.

Wilcock, P.R.; Crowe, J.C. (2003). Surface-based transport model for mixed-size sediment. *Journal of Hydraulic Engineering 129(2)*: 120-128.

Williams, G.J. (1997). Ngaruroro River Gravel Resources: Assessment of Gravel Supply and Extraction Availability. *Williams Consultants, Otaki*.

Williams, G.J. (1991). Heretaunga Plains Gravel Resources: Evidence to the Planning Tribunal. *Williams Consultants, Otaki*.

Williams, G.J. (1987). The Ngaruroro River Scheme: Investigations and Review. *Hawkes Bay Catchment Board, Napier*.

Williams, R.D.; Brasington J.; Vericat, D.; Hicks, M. (In preparation). Hyperscale monitoring and modelling of braided Rees River, New Zealand. *Earth Surface Processes and Landforms*.

Wu, W. (2008). Computational River Dynamics (p. 494). Taylor & Francis Group.