Journal of Hydrology (NZ) 50 (1): 241-256 2011

Quantification and validation of a sediment budget for the lower Hutt River, Wellington, New Zealand

Jack McConchie,[1] Grant Webby,[1] Francie Morrow,[1] Franciscus Maas[1] and Jacky Cox[2]

[1] *Opus International Consultants Ltd, Wellington, PO Box 12003, Wellington 6144, New Zealand. Corresponding author: Jack.McConchie@opus.co.nz*

[2] *Greater Wellington Regional Council, PO Box 11646, Wellington 6142, New Zealand.*

Abstract

A sediment budget for the Hutt River was developed to assess the volume of sediment that needs to be removed to maintain hydraulic efficiency of the channel, and the potential environmental effects of sediment extraction along the river and at its mouth. The transport of both suspended sediment and bedload was calculated using the characteristics of the available sediment and flow records from Taita Gorge. There are no significant inputs of either sediment or water downstream of this location. The volume of suspended load was estimated using a sediment rating curve. Bedload transport was estimated using a range of theoretical equations relating sediment transport to flow and channel parameters, and the characteristics of the material forming the river bed and banks. The sediment transport models were validated using the cumulative change in sediment volume determined from repeated cross-section surveys, and the volume of sediment extracted from the river.

Analysis of the sediment budget indicates that the average annual sediment transport, including suspended and bedload, downstream of Taita Gorge is approximately 104,000 m^3/year. The calculated average sediment transport rate compares favourably to that derived from the analysis of channel cross-sections and sediment extraction records (approximately 88,000 m^3/year). The difference is from material deposited downstream of the analysed cross-sections (and beyond the river mouth) which was not quantified, and also from errors in the cross-section data analysis and the records of sediment extraction volumes.

Only 8% of the material transported downstream is bedload; the remaining 82% is suspended sediment. These estimates are consistent with other New Zealand data. The total volume of suspended sediment and bedload transported exceeds that removed for flood protection works, and extracted at the river mouth. The excess sediment contributes to aggradation of the river bed and harbour floor.

Sediment transport varies considerably over time and is controlled largely by the number, magnitude, and duration of floods. The annual rate of sediment transport since 1987 has ranged from 75,000 to 139,000 m^3. Lower than average rates since 2004 reflect the lack of significant floods over this period.

The calibrated sediment budget for the lower Hutt River is valuable for guiding river management and flood mitigation works, and assessing the potential environmental

effects of human activities such as sediment extraction at the river mouth.

Introduction

The interaction of stream flow with the landscape, and the erosion and transport of material, produce distinctive changes down a river profile. In general, rivers are characterised by erosion and transport of material from the upper catchment, conveyance through the mid reaches, and deposition within the lower channel and at the river mouth. This sequence is apparent within the Hutt catchment, just north of Wellington, New Zealand (Fig. 1).

River valleys reflect the interaction of the energy of flow with the resistance and properties of the material forming the catchment and the bed and banks of the channel. This interaction is inherently complex, with numerous thresholds, positive and negative feedbacks, and considerable variability. One way to simplify this complexity is through the use of a sediment budget.

The Hutt catchment has been affected by a number of climatic fluctuations which affect the erosion and transport of material. During glacial periods erosion processes were greatly accelerated in the Tararua Ranges; enhanced by reduced vegetation cover. This provided a large amount of sediment which was transported out of the mountains by the river. Reduced channel gradient and energy in the lower valley led to much of this material being deposited in an extensive flood plain and terraces. During interglacial periods, such as

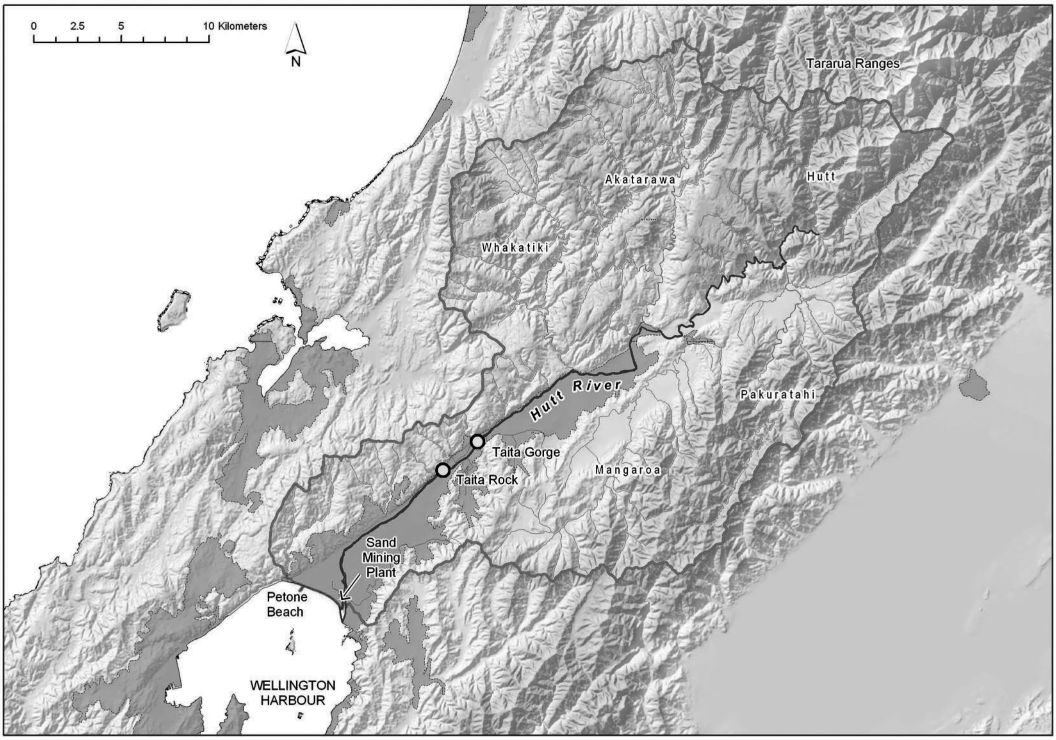

Figure 1 – Location of the Hutt catchment and relevant sites.

(Source: Greater Wellington Regional Council, 2011) at present, vegetation cover in the catchment increases, reducing the rate of erosion. In response to the reduced sediment supply, the Hutt River has become incised into its earlier alluvial deposits and now largely flows within bed and banks composed of material that it has eroded, transported, and deposited previously. Consequently this material is susceptible to erosion and transport further downstream during high-energy floods.

Much of the sediment currently being transported down the Hutt River is deposited in the vicinity of the river mouth, and in Wellington Harbour. This material includes a significant proportion of sand-sized particles, which are a valuable resource for the building and construction industries. Resource consents are required for the extraction of this sediment, and for maintenance of the hydraulic efficiency of the channel for flood mitigation. These consents will only be granted if it can be shown that any adverse effects of these activities are less than minor. Assessment of these effects requires an understanding of the sediment budget of the river so that any removal of sediment can be placed in context.

Background

Every river has the capacity to erode, transport, and deposit sediment. Water flowing in an open channel is subject to two principal forces; gravity and friction. The relationship between these forces determines the energy of the flowing water, and consequently its ability to erode and transport sediment.

The erosive potential of this hydraulic action is quantified by the average shear stress exerted on the channel boundaries by the flow. Whether this hydraulic shear is sufficient to initiate bed or bank erosion depends on its magnitude relative to the forces resisting erosion. These forces of resistance are a function of the characteristics of the bed and bank material.

Although properties other than size influence particle resistance (i.e., particle density and shape, degree of packing, cementation etc.), size is often used as a convenient measure from which to estimate sediment entrainment thresholds. These thresholds are usually expressed in terms of either the critical shear stress, or the flow velocity. Shear stress thresholds summarise the actual forces acting to dislodge or entrain particles. Velocity thresholds describe the velocity of flow needed to exert sufficient force to dislodge or entrain particles.

Entrainment thresholds are commonly defined for the median size (D_{50}) of the bed and bank material. In some situations, including the Hutt River, coarser material can form a protective armouring layer on the surface of the river bed. Therefore it is useful to estimate entrainment velocities for the D_{90} grain size (the coarsest 10% of material). It is also important to note that although intermediate particle sizes (i.e., fine sand or coarse silt) are generally the easiest to entrain; smaller particles, once entrained, remain in suspension much longer.

The total amount of sediment transported by a river can be divided into components depending on its mode of transport. These components are solution or dissolved load, wash load, suspended load, and bedload. Solution and wash load are not generally controlled by stream power but by the availability of material. Suspended and bedload, however, are controlled by both material availability and stream power. The distinction between the modes of transport, however, is rather arbitrary, with material moving from one mode to another as a function of available energy.

Bedload transport is often assumed to be a function of energy – both the energy necessary to entrain particles and the energy necessary to transport them. However, in many situations the transport rate also depends on the availability of material (i.e., it is supply limited). The Hutt River is not generally supply limited, as in the lower valley its bed and banks are composed of material it has previously eroded, transported, and deposited.

The total sediment load of the Hutt River is all the inorganic material which is transported by the flowing water, i.e., boulders, sand, silt, clay, etc. However, from the perspective of maintaining the hydraulic efficiency of the channel and assessing the potential environmental effects of sediment extraction, it is the suspended and bedload components that are critical. Derivation of a sediment budget for the Hutt River has therefore focused on quantifying these components of the sediment load. Solution and wash load are transported beyond the river mouth and therefore do not affect the channel form.

Study area

The Hutt River, with a catchment area of 656 km², has its headwaters in the Tararua Ranges and drains southwest into Wellington Harbour. The catchment is predominantly rugged hill and mountainous terrain (50% has slopes between 25 and 35°), with the Hutt Valley forming the largest flat area. The catchment includes agricultural, scrubland, residential, commercial, and industrial land uses in the lower areas; and predominantly forest and scrubland in the hill and mountainous terrain. The main stem of the Hutt River is 55 km long, and for much of its length it is aligned with the Wellington Fault. In its lower reaches the river flows across an extensive coarse-grained alluvial gravel flood plain formed during past glacial climatic periods. The flood plain is currently being eroded, and the bed degraded, along some reaches. The catchment has a population of approximately 154,500 (updated from 2006 census), of whom about 98,000 live on the lower flood plain (McConchie, 2001).

Previous work

A comprehensive report on the characteristics and sedimentation of the Hutt River was commissioned by the Wellington Regional Council (Williams, 1991). That report discusses the river characteristics (i.e., geological setting, natural condition of the main channel, channel changes since European colonisation, the form of the natural meander patterns, channel resistance, and variations in channel geometry) and provides a sedimentation study (i.e., an estimate of suspended and bed material transport rates). The rating curves derived by Williams (1991) have been used in this current study to estimate the volume of suspended sediment transported down the Hutt River between 1987 and 2009.

Previous resource consents granted for sediment extraction and the dumping of waste by-product included conditions requiring specific monitoring of the potentially affected environments. This included cross-sectional surveys of 313 profiles of the river bed along the lower 33.5 km of the Hutt River at 5-yearly intervals, full hydrographic surveys of the greater river mouth area at 10-yearly intervals, aerial photography of the greater river mouth area at 2-yearly intervals, and six beach profile surveys, including photographs and sediment size analysis of samples from Mean Sea Level (MSL) on each profile, at 6-monthly intervals.

A gravel analysis of the Hutt River from 1987-2009 was completed by Gardner (2010). The report compiles, analyses, and presents data from the 1987, 1993, 1998, 2004 and 2009 cross-section surveys. Volume changes calculated in Gardner (2010) were used to calibrate the results of bedload and suspended sediment calculations in this study.

Methods

Sediment budgets

Developing a sediment budget consists of evaluating the fluxes, sources, and sinks of sediment from different processes that can lead to the addition and subtraction of material within the control volume (i.e., the area of interest). Sediment may be temporarily stored and remobilised several times; for example within the bed, banks, and flood plain, before exiting the control volume (Charlton, 2008; Knighton, 1998).

There are two ways in which a sediment budget can be constructed:

1. measurement and quantification of the changes in the surface of the control volume; and
2. assessment and quantification of exchanges of material within the flow.

The methods adopted in the current study were a mix of both approaches. Sediment transport rates were quantified by assessing the energy of the flow and the resistance of the available material. These rates were then validated by comparing them to estimates of material exchange through changes in the surface of the control volume, i.e., by analysis of repeated cross-section surveys.

The downstream boundary of the control volume in the current study is the Hutt River mouth, and the upstream boundary is at Taita Rock; about 2.3 km downstream of the Taita Gorge flow gauging station (Fig. 1). This site marks the approximate boundary between bed degradation upstream and aggradation downstream, and where the surveyed river cross-sections have remained fairly constant over time. It is also well beyond the upstream limit of backwater influence of tide level at the river mouth during extreme floods.

Sediment transported down the Hutt River as suspended and bedload includes silt, sand, and gravel. This material is eroded either from the contemporary flood plain, or the slopes of the upper catchment. The method by which this material moves depends largely on its particle size and the energy of the flow in the river; consequently, sediment transport processes tend to operate only during flood conditions. Knowledge of the flow regime, and how this varies over time, is therefore fundamental to understanding sediment transport processes and dynamics.

Streamflow

The most downstream flow gauging station on the Hutt River is at Taita Gorge, approximately 12 km upstream from the river mouth. Flows have been measured at Taita Gorge since 1979 and there are no significant inputs of either water or sediment downstream of this location (Fig. 1). This record therefore provides a reliable basis for assessing the variability of the flow regime of the lower Hutt River. All calculations of bedload and suspended load transport have been undertaken using the flow record from Taita Gorge and sediment characteristics over the control reach.

The highly variable flow regime of the Hutt River (Fig. 2) is typical of a river draining a mountainous catchment. There are occasional large floods interspersed with long periods of relatively low flow. Consequently, the median flow is significantly less than the mean, as it is less affected by the flood flows (14.2 m^3/s compared to 24.8 m^3/s). Over the past 31 years flows in the Hutt River have varied from as low as 1.6 m^3/s to approximately 1562 m^3/s.

Using the sediment particle entrainment thresholds defined by Williams (1991) the upper threshold of 350 m^3/s is exceeded 0.3% of the time, and the lower threshold (200 m^3/s) 0.8% of the time (Fig. 2). Notwithstanding these relatively short periods of bedload transport, the large amount of available energy is sufficient to erode and transport a significant volume of material.

As indicated earlier, there is a strong relationship between flow velocity and

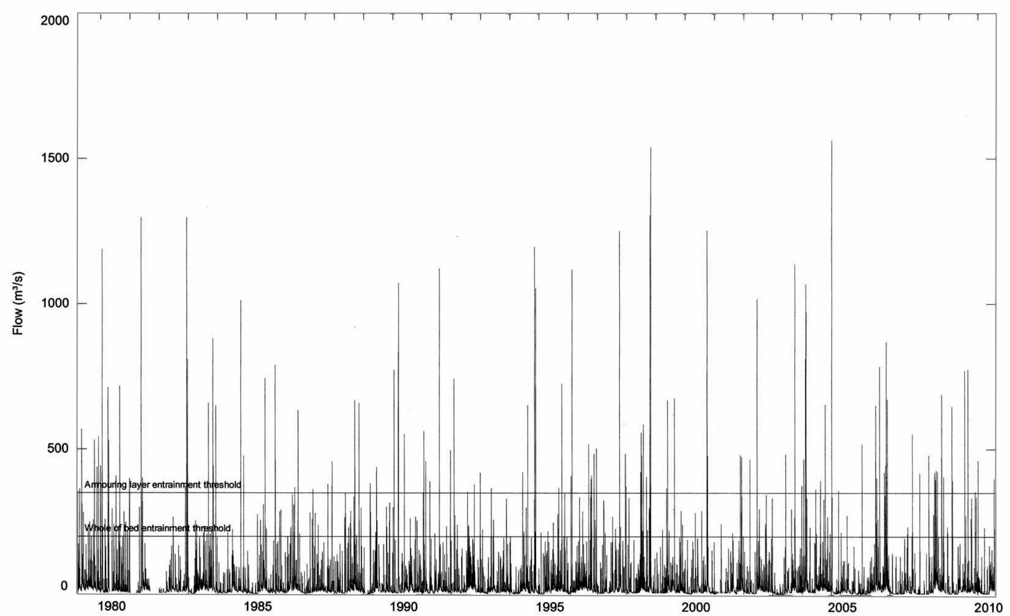

Figure 2 – Flow record for the Hutt River at Taita Gorge (1979–2010); including the two bedload entrainment thresholds from Williams (1991).

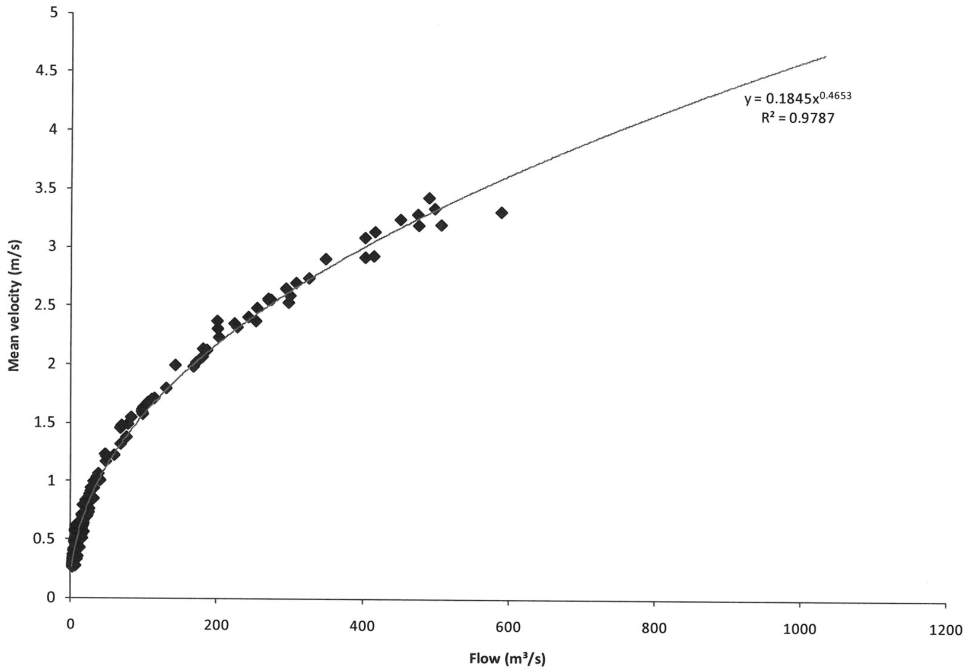

Figure 3 – Relationship between flow and mean velocity for the Hutt River at Taita Gorge.

the size of material that can be eroded and transported. Flow gauging data from Taita Gorge were used to develop a relationship between flow and average velocity (Fig. 3). While the maximum velocity is actually more critical to particle erosion and transport, these data are not available. The use of the mean velocity consequently produces a conservative estimate of the maximum particle size likely to be transported at a given flow.

The use of the mean velocity of given flows at Taita Gorge, and particle entrainment threshold information, allows estimation of the likely maximum particle size able to be transported under particular conditions (Table 1). This relationship assumes a specific density of the particles of 2.65 g/cm^3. This value is consistent with the specific density of quartz and feldspar, the predominant minerals in the greywacke that forms the bulk of sediment within the Hutt River.

From Table 1 it can be seen that as flow increases so does the mean velocity, and as a result, the size of particles that can be transported. At a flow of 200 m^3/s, the mean velocity at Taita Gorge is 2.2 m/s. Flows of this magnitude can theoretically transport particles up to about 75 mm in diameter. At flows of 1600 m^3/s, approximately the largest flow recorded at Taita Gorge, the mean velocity is 5.7 m/s and particles up to 500 mm in diameter can be moved.

Table 1 – Maximum size of sediment theoretically able to be transported at various flows.

Flow (m^3/s)	Mean velocity (m/s)	Size (mm)
100	1.6	60
200	2.2	75
400	3.0	110
600	3.6	150
800	4.1	200
1000	4.6	260
1200	5.0	330
1400	5.4	420
1600	5.7	500

Sediment transport modelling

Bedload transport

Bedload transport through the control reach was assessed using BAGS (Bedload Assessment for Gravel-bed Streams) sediment transport modelling software (Pitlick *et al.*, 2009). BAGS is now regarded as one of the 'industry standards' with regard to bedload transport modelling. Transport capacities are calculated on the basis of field measurements of energy of flow, channel geometry, average reach slope, and the bed material properties (by splitting the bed material into discrete size fractions).

There are no actual bedload measurements which can be used for calibration. The water depths computed by BAGS were therefore used as a calibration check by comparing the results to those from a MIKE11 hydraulic model (DHI, 2003) of the Hutt River developed by Greater Wellington Regional Council. The two sets of results are very similar (Fig. 4). This indicates that BAGS is interpreting the cross-section and hydraulic data appropriately, and by implication the bed shear stresses inducing sediment motion.

There are limited data available regarding the characteristics of the bed and bank material in the vicinity of Taita Gorge. Williams (1991) produced sediment size distribution curves of both the armouring layer and the whole of the bed for cross-sections approximately 1 km (X-section 1120) and 5 km (X-section 720) below Taita Gorge. These data were therefore used to estimate a sediment distribution curve for the control reach.

Since BAGS provides equations for either the armouring layer (i.e., Parker, 1990; Wilcock and Crowe, 2003) or the substrate (i.e., Parker *et al.*, 1982; Parker and Klingeman, 1982) sediment grading curves

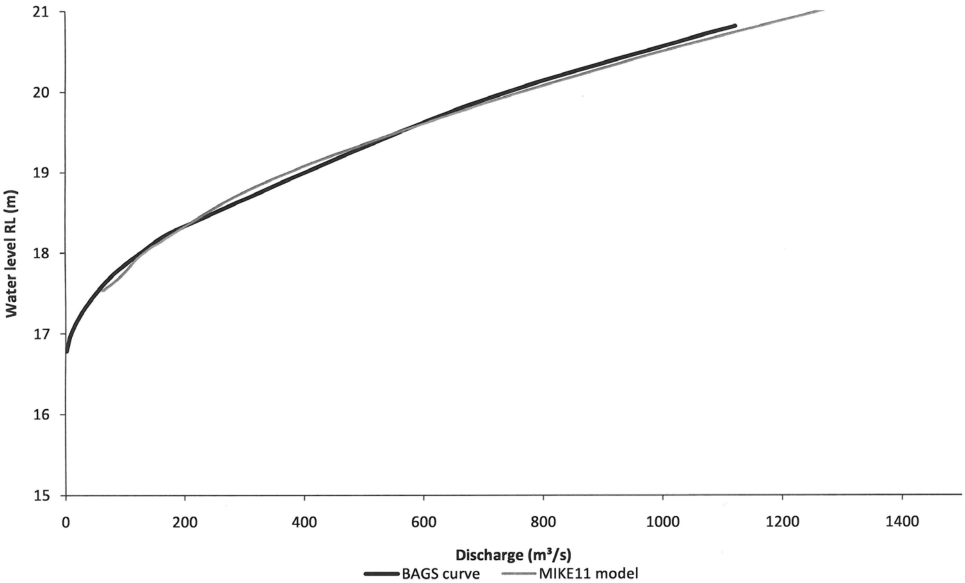

Figure 4 – Modelled discharge/water level rating curves. The BAGS curve is based on a uniform flow assumption. The MIKE11 model curve was obtained from model simulation results provided by Greater Wellington Regional Council.

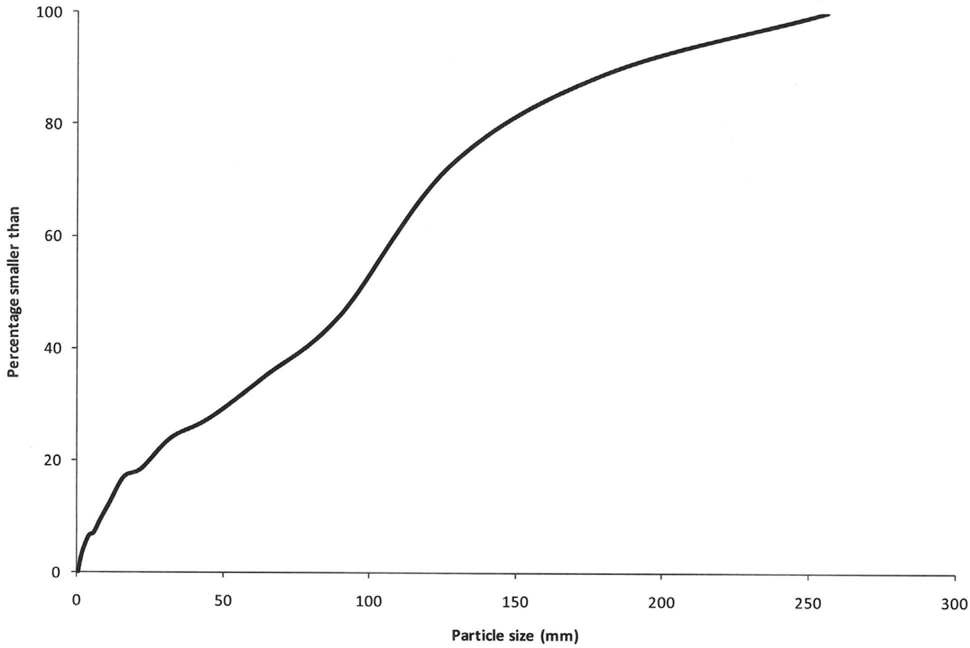

Figure 5 – Composite sediment grading curve derived to characterise material available for transport through the control reach.

for both were required. For the substrate equations the whole of bed curve from cross-section 720 was used. Cross-section 720 is about mid-way down the control reach and so should be indicative of 'average' conditions.

Initially, the sediment size distribution of the armouring layer of the control reach was estimated by drawing an average curve between those provided for cross-sections 720 and 1120. This approach, however, tended to over-emphasise the significance of the larger material at cross section 1120. To overcome this problem, a composite curve was developed using the average of cross-sections 720 and 1120 for particles sizes up to 100 mm, and the results from cross-section 720 for the larger particle sizes (Fig. 5). This composite curve is considered to be a good representation of the 'average' armouring material over the control reach. The slightly smaller estimated size of the armouring layer using this curve results in higher estimated rates of bedload transport (Fig. 6).

It should be noted that these sediment grading curves characterise the bed material and not necessarily the total load transported through the control reach. Consequently, they are biased towards the coarser material. For example, only approximately 6% of the armouring material and 18% of the whole of bed material is sand-size or finer (i.e., <5 mm). At the river mouth, approximately 89% of the material deposited on the river bed is less than 5 mm in diameter.

Because of the sensitivity of bedload transport to flow velocity (i.e., energy) the effect of increasing the resolution of the flow distribution curve was also assessed. Increased sensitivity and resolution over the high-flow portion of the flow distribution resulted

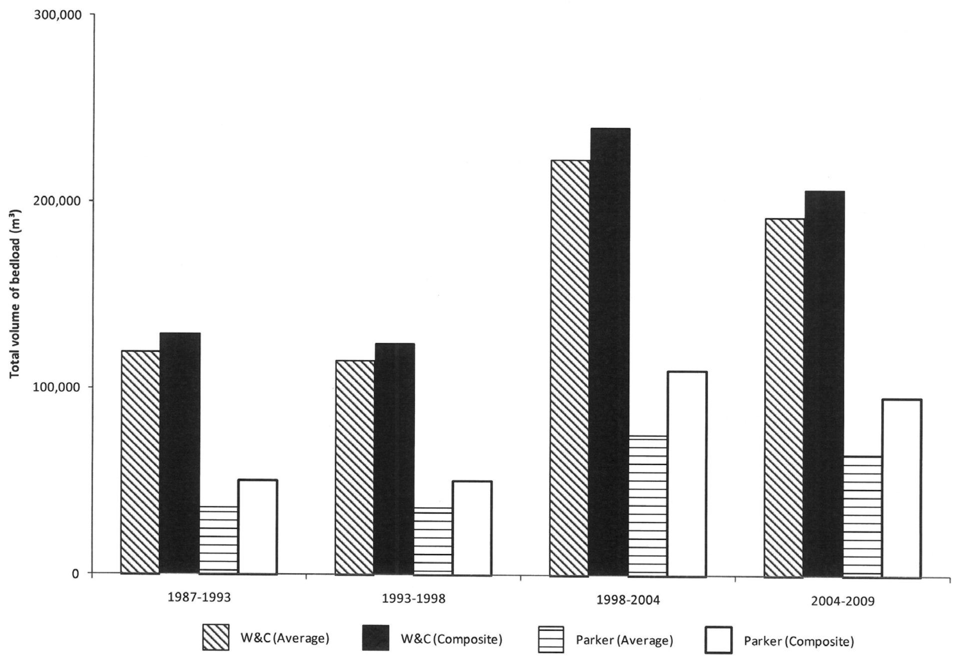

Figure 6 – Effects of different sediment grading curves on bedload transport volumes. The composite grading curve, derived to reflect bed material over the control reach, produces higher transport rates. The W&C and Parker bedload transport volumes are estimated using equations from Wilcock and Crowe (2003) and Parker (1990).

in estimates of significantly less bedload transport (Fig. 7). This is because the simple linear interpolation of lower resolution data effectively 'increases' the apparent frequency of higher flow velocities. This causes a significant increase in the estimated sediment transport rate because of the nature of the relationship between velocity and particle entrainment thresholds, as discussed earlier.

BAGS provides the choice of six bedload transport equations, developed specifically for gravel-bed rivers (Fig. 8). After calibration it was found that the equation proposed by Wilcock and Crowe (2003) for mixed sand and gravel transport was the most suitable for the Hutt River. This is likely a result of the relatively high percentage of sand present in the Hutt River, and its movement is more accurately modelled by the Wilcock and Crowe (2003) equation.

To compare bedload transport rates with changes in various measured channel cross-sections, total bedload transport was calculated over each inter-survey period for the channel cross-sections (1987–1993, 1993–1998, 1998–2004 and 2004–2009). The results were converted from a bedload transport rate (kg/s or tonnes/day) to a total bedload volume over each inter-survey period (Table 2) using a factor of 1600 kg/m^3 (Ministry of Works and Development, 1973).

Suspended sediment transport

As well as bedload, consideration of the suspended sediment load is also required to develop a complete sediment budget. Therefore, the relationship between suspended sediment transport and flow developed by Williams (1991) was used, in combination with the flow regime from Taita Gorge, to derive the volume of suspended

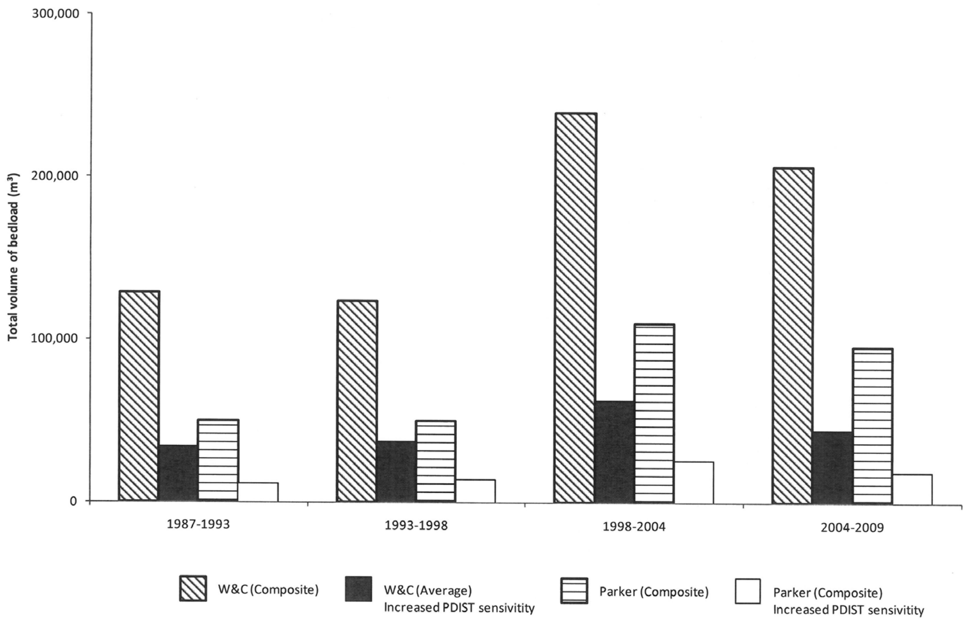

Figure 7 – Effects of increased sensitivity at high flows within the flow distribution curves. Increased sensitivity of the flow duration curve reduces the volume of sediment transport. The W&C and Parker bedload transport volumes are estimated using equations from Wilcock and Crowe (2003) and Parker (1990).

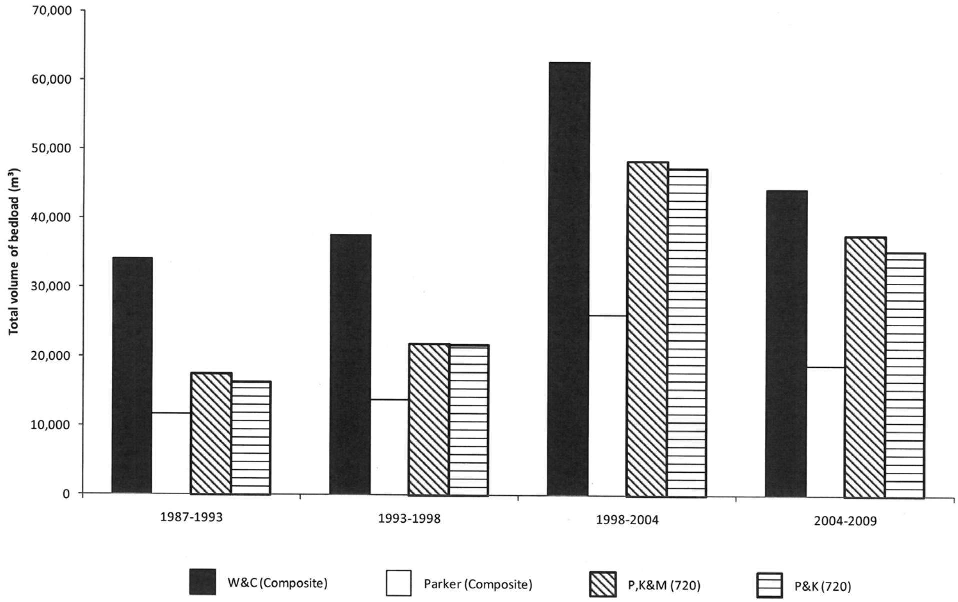

Figure 8 – Results of BAGS modelling using the composite sediment size curve and increased high-end sensitivity flow distribution curve for each inter-survey period. The W&C, Parker, P,K&M and P&K bedload transport volumes are estimated using equations from Wilcock and Crowe (2003), Parker (1990), Parker, Klingeman, and McLean (1982) and Parker and Klingeman (1982) respectively.

sediment transported over each inter-survey period (Table 2).

Total sediment transport

The total volume of sediment transported by the Hutt River through the control reach over each inter-survey period is the sum of both the bedload and suspended sediment volumes (Fig. 9). The average rate of sediment transport over the 22-year period was approximately 104,000 m^3/year. This calculation does not include the dissolved and wash load, which is transported beyond the control reach and into Wellington Harbour. The values of sediment transport modelled from the flow record agree very favourably

Table 2 – Modelled sediment load over each inter-survey period.

Period	Suspended sediment volume (m^3)	Bedload sediment volume (m^3)	Total modelled sediment – bed and suspended (m^3)	Bedload as a percentage of total volume (%)	Net aggradation from survey data (m^3)
1987-1993	409,000	34,200	443,000	7.7	131,300
1993-1998	477,000	37,500	514,000	7.3	156,600
1998-2004	770,000	62,700	833,000	7.5	282,000
2004-2009	419,000	44,300	463,000	9.6	9,800

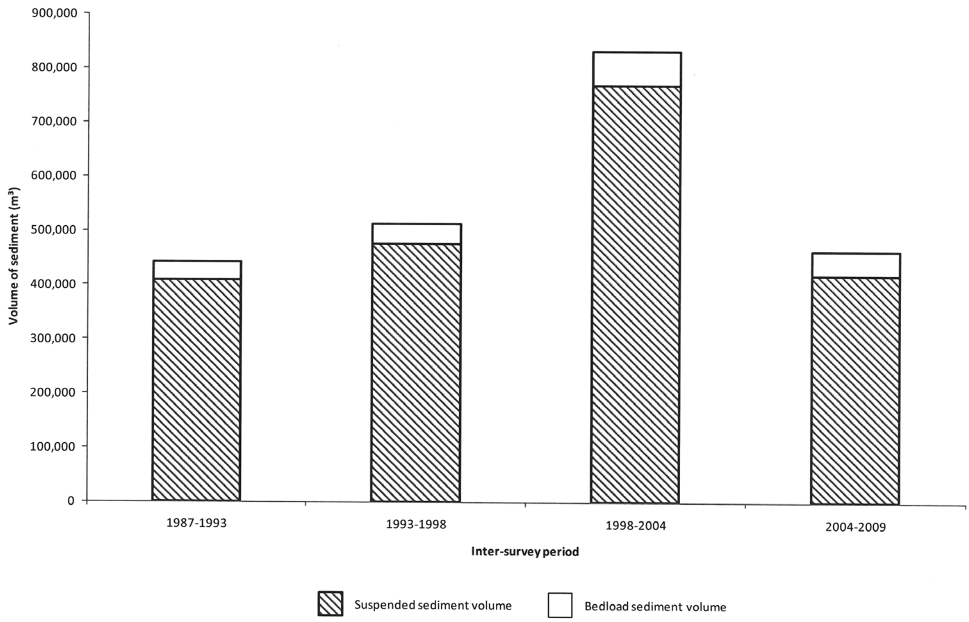

Figure 9 – Suspended sediment and bedload transport through the control reach over each inter-survey period.

with those derived from the summation of sediment aggradation and extraction volumes using the cross-section survey data discussed later. They are therefore considered realistic.

Figure 9 and Table 2 show that bedload makes up about 8% of the total load, with the remainder being composed of suspended load. This is consistent with other estimates from New Zealand, which indicate that bedload transport is typically 3–10% of the total load (Hicks and Griffiths, 1992).

Calculation of sediment budget

Analysis of cross-sections

The Greater Wellington Regional Council (GWRC) regularly surveys cross-sections along the Hutt River. The data from these surveys are used to analyse trends in the movement of gravel bed material, and bed aggradation and degradation along the river.

Using the changes in the various cross-sections between successive surveys, cumulative sediment volume change curves were produced for each inter-survey period (Fig. 10). These curves start at Taita Rock and terminate adjacent to Winstone's sand extraction plant, just upstream of the river mouth. The channel between Taita Gorge and Taita Rock has been in quasi-equilibrium over the duration of the surveys. A positive slope with increasing downstream distance on these curves indicates aggradation of the bed while a negative slope reflects degradation.

Figure 10 shows that in general the bed of the Hutt River downstream of Taita Rock has been aggrading over time. However, over the 2004–2009 inter-survey period, degradation is apparent over the 4 km immediately downstream of Taita Rock. Further downstream the bed has continued to aggrade. The largest net increase in sediment aggradation occurred over the 1998–2004 inter-survey period. This is likely related to the number of significant floods over that period (Fig. 2).

The last column of Table 2 summarises the net aggradation volumes over the inter-survey

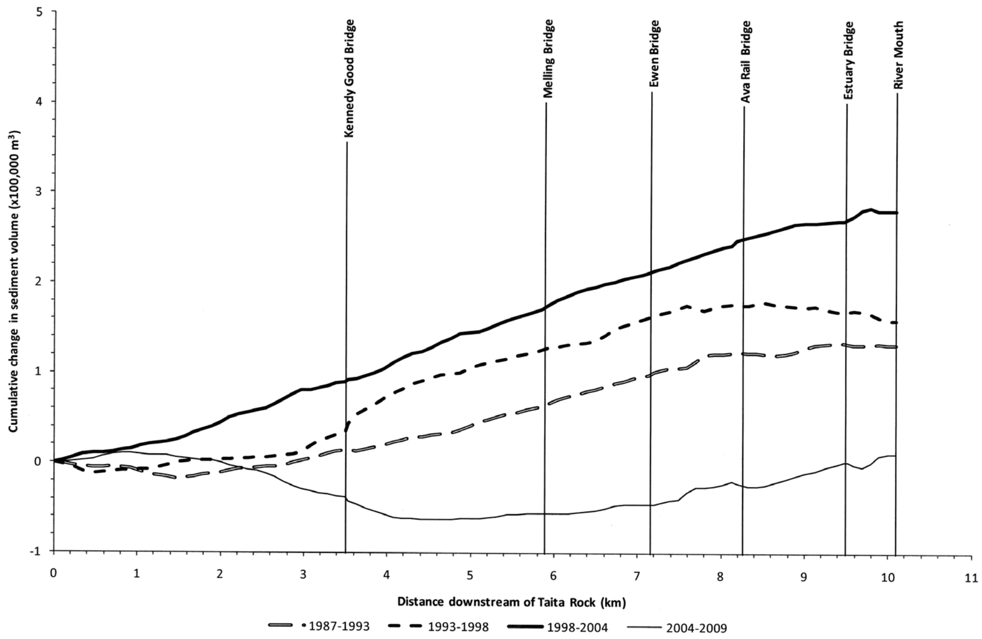

Figure 10 – Cumulative change in sediment volume in Hutt River downstream of Taita Rock for each inter-survey period from 1987–2009.

periods. It should be noted that these net aggradation volumes exclude any sediment deposited downstream of the Winstone's sand extraction plant.

The total amount of sediment deposited within the Hutt River downstream of Taita Rock, however, includes not only the sediment still remaining in the channel but also that extracted for various reasons, e.g., flood control and sand extraction at the river mouth. The average annual volume of sediment therefore deposited over each inter-survey period is summarised in Table 3 and Figure 11.

Comparison of different data sources

The volumes of sediment transported during each inter-survey period have been transformed into an annual average value. These are then compared with those derived

Table 3 – Average annual sediment balance for the control volume.

Component	Sediment volume (m^3/year)				
	1987-1993	**1993-1998**	**1998-2004**	**2004-2009**	**1987-2009**
Net aggradation	22,200	33,600	47,000	1,960	26,900
Extraction					
– River	10,200	0	7,780	45,200	15,400
– Mouth	47,200	47,200	43,900	44,100	45,500
Total deposition	79,600	80,800	98,700	91,300	87,800

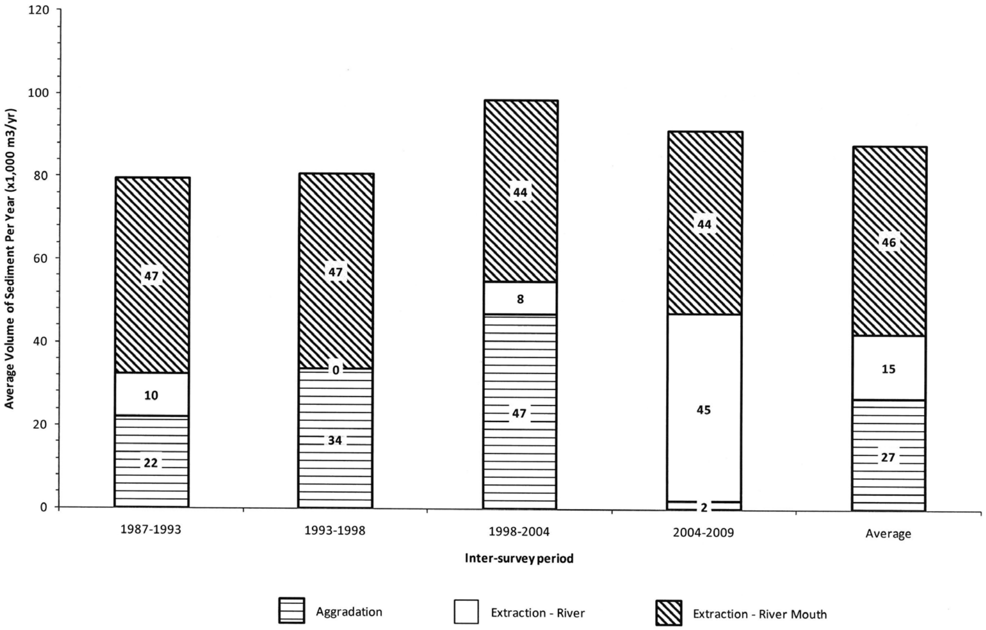

Figure 11 – Destination of the average annual sediment deposited downstream of Taita Rock.

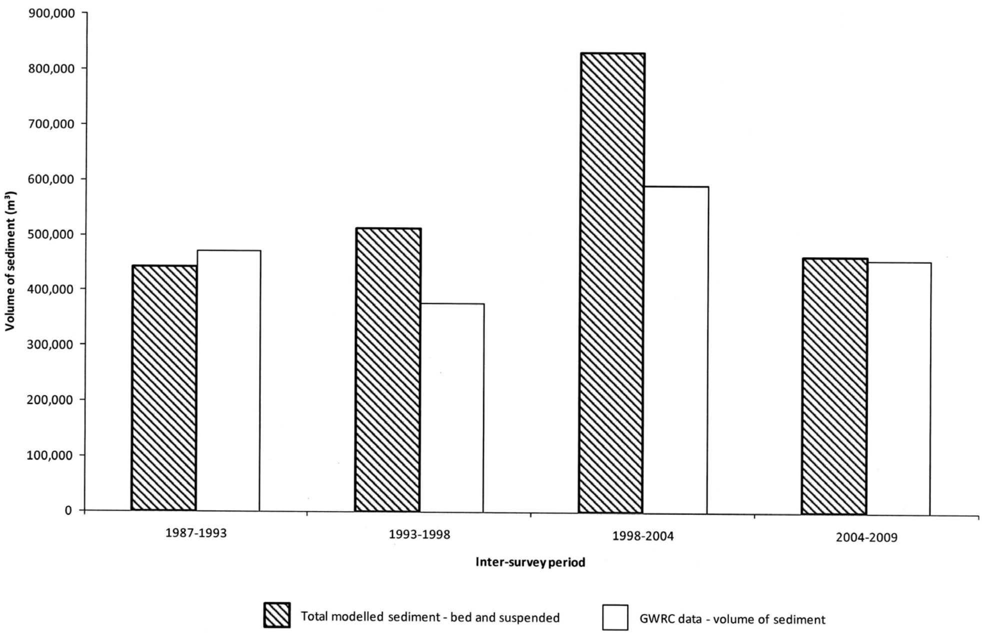

Figure 12 – Comparison of total sediment volumes estimated from modelling and analysis of sediment aggradation and extraction.

Table 4 – Annual average sediment volumes.

Period	Annual average suspended sediment volume (m^3/year)	Annual average bedload sediment volume (m^3/year)	Annual average total sediment load (m^3/year)	Annual average GWRC total volume (m^3/year)
1987-1993	69,200	5,780	75,000	79,600
1993-1998	102,000	8,050	110,000	80,800
1998-2004	129,000	10,500	139,000	98,700
2004-2009	83,900	8,860	92,700	91,200
Long term 1987-2009	***96,300***	***8,300***	***104,000***	***87,800***

from the analysis of cross-section changes and sediment extraction over the same period (Figure 12 and Table 4).

There is a high degree of variation in the amount of suspended sediment, bedload, and consequently total load transported over each inter-survey period. This is to be expected because of the variation in the flow regimes over these different periods; particularly the number, magnitude, and duration of flood events. The modelled results show a greater degree of variation than those derived from the cross-section analysis. This is because of the greater sensitivity of the sediment transport modelling, which is based on the actual flow regime and energy of the river. The results from the analysis of cross-sections are the average net change in material over the inter-survey period and not necessarily a measure of the total sediment transport.

These results show that the annual transport of sediment through the control reach was relatively constant over the first two inter-survey periods, i.e., between 1987 and 1998. The transport of sediment was highest over the 1998–2004 inter-survey period. The amount of sediment deposited during the inter-survey periods is directly related to flood activity.

Conclusions

Estimates of both bedload and suspended sediment transported through the control reach, and the resulting sediment budget, indicate that the average annual sediment transport rate through the control reach from 1987 to 2009 was approximately 104,000 m^3/year. The total load is composed of all material transported as either suspended load or bedload. The calculated sediment transport rate (104,000 m^3/year) compares favourably to that derived from an analysis of channel cross-sections surveyed at 5-yearly intervals (i.e., approximately 88,000 m^3/year). This value is likely to be a slight under-estimate, as it excludes any allowance for sediment aggradation in the 660 m long reach downstream of the Winstone's sand extraction plant. Of the total sediment transport, approximately 8% is bedload. The remaining 82% is suspended sediment. These estimates are consistent with other New Zealand data.

The annual rate of sediment transport since 1987 has ranged from 75,000 to 139,000 m^3. Annual sediment transport is controlled largely by the number, magnitude, and duration of floods. Sediment which accumulates at the river mouth reflects the average rates of sediment transport over time, rather than the sediment pulse from a specific year.

While the average rate of sediment accumulation provides an indication of long-term trends of either aggradation or degradation, there is a high degree of inter-annual variability. Lower-than-average rates of sediment accumulation since 2004 reflect the lack of significant floods over this period. It is likely that an average annual sediment transport rate of approximately 104,000 m^3 is indicative of the long-term sediment transport regime in the lower Hutt Valley.

References

Charlton, R. 2008: *Fundamentals of fluvial geomorphology*. Routledge, London.

DHI 2003: MIKE 11 – a modelling system for rivers and channels. User Guide, DHI Software, 2003.

Gardner, M. 2010: Hutt River floodplain management plan: Hutt River gravel analysis 1987-2009. Report: N/03/09/05. Greater Wellington Regional Council, Wellington, New Zealand.

Hicks, D.M.; Griffiths, G.A. 1992: Sediment load. *In*: Mosley, M.P. (*ed.*) *Waters of New Zealand*. New Zealand Hydrological Society: 229-248.

Knighton, D. 1998: Fluvial forms and processes – a new perspective. Arnold Publishing, London, 383 p.

McConchie, J.A. 2001: Water transport processes. *In*: A. Sturman, A.; Spronken-Smith, R. (*eds.*) The Physical Environment – a New Zealand Perspective. Oxford University Press.

Ministry of Works and Development 1973. Retaining wall design notes. Civil Division Publication CDP 702/C, New Zealand Ministry of Works and Development, Wellington.

Parker, G. 1990: Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research 28*: 417-436.

Parker, G.; Klingeman, P.C. 1982: On why gravel bed streams are paved. *Water Resources Research 18(5)*: 1409-1423.

Parker, G.; Klingeman, P.C.; McLean, D.L. 1982: Bedload and size distribution in paved gravel bed streams. *Journal of Hydraulics Division, ASCE. 108*: 544-571.

Pitlick, J.; Cui, Y.; Wilcock, P. 2009: Manual for computing bed load transport using BAGS (Bedload Assessment for Gravel-bed Streams) Software. Gen. Tech. Rep. RMRS-GTR-223. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 45 p.

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

Williams, G.J. 1991: Hutt River floodplain management plan: Hutt River characteristics and sedimentation. G & E Williams Consultants, June 1991.