HUTT RIVER MOUTH

Fluvial sediment transport

Prepared for Greater Wellington

Hutt River Mouth

Fluvial sediment transport

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Executive summary

The potential transport of both bedload and suspended load has been calculated for the lower Hutt River. These estimates are based on the size characteristics of the sediment and the flow record from Taita Gorge. This is considered appropriate given that there are no significant inputs of either sediment or water downstream of this location. The volume of suspended load has been estimated using a sediment rating curve. Bedload transport has been estimated using a range of theoretical equations relating sediment transport to flow and channel parameters, and sediment size characteristics of the river bed and banks.

The results indicate that:

- The average annual sediment transport past Taita Gorge is 104,564m^3/year. The total load is composed of all material transported as either suspended load or bedload.
- The sediment transport rate calculated compares favourably to that calculated in Opus (2010a) of 87,835m^3/year. The difference relates largely to material deposited downstream of cross-section 30 and beyond the river mouth. This material is not considered in Opus (2010a), although it is discussed in Opus (2010b).
- Of the total sediment transport approximately 8% is bedload. The remaining 82% is suspended sediment. These estimates are consistent with other New Zealand data.
- There is a high degree of variability in sediment transport. This relates to flow variability within the Hutt River.
- The annual rate of sediment transport since 1987 has ranged from 75,000 to 139,000m^3.
- Annual sediment transport is controlled largely by the number, magnitude, and duration of flood events.
- 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, there is a high degree of inter-annual variability.
- Lower than average rates of sediment accumulation since 2004 likely reflects the lack of significant flood events over this period.
- It is likely that an average annual sediment transport rate of approximately 88,000m^3 is indicative of the long term sediment transport regime.

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1 Background

Understanding the sediment transport processes operating within the Hutt River, and the volume of material involved, is critical to making an assessment of the environmental effects of sediment mining from the river mouth. This report forms part of a series of three reports which investigate different aspects of the sediment budget for the Hutt River. In this particular report the sediment transport processes are reviewed, and the amount of material transported as bedload and suspended load quantified.

1.1 Fluvial processes

Water flowing in an open channel is subject to two principal forces: gravity (in the down slope direction) and friction (opposing the down slope motion). The relationship between these forces ultimately determines the energy of the flowing water, and consequently its ability to erode and transport sediment. The erosive potential of hydraulic action is quantified by the average shear stress (or force per unit area) exerted on the channel boundaries by the flow. This average boundary, or bed shear stress, is affected locally by turbulent fluctuations in the flow and secondary flow patterns. 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.

The interaction between near-bank fluvial processes and the bank material is complex. This is because the bed topography, resistance to flow (roughness), sediment type, and the water and sediment motion are all highly variable in both space and time. Changes in any of these parameters can significantly influence both the magnitude, and the relative importance, of the hydraulic forces on erosion and sediment transport. Although properties other than size influence particle mobility (i.e., particle density and shape, degree of packing, cementation) for fine sediments in particular, size is often used as a convenient measure from which to estimate likely 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.

A critical aspect of fluvial processes associated with flow hydraulics is sediment transport. Every river has the capacity to erode, transport, and deposit sediment. A wide range of properties control the amount and type of sediment transport. The actual mode of transport depends on the interaction of available energy and material resistance. The total load of a river can be divided up into components depending on their mode of transport (Figure 1.1).

1. Solution/Dissolved load - this includes all particles which are actually dissolved in the flow, i.e., the ions in the water. Dissolved load is derived from several sources: rock and soil weathering, from the atmosphere, and from human activity on the land (e.g., fertilizers, industrial plants). The majority of dissolved load is supplied to the river by subsurface flows as this water has had the longest contact time with the soil and rock.

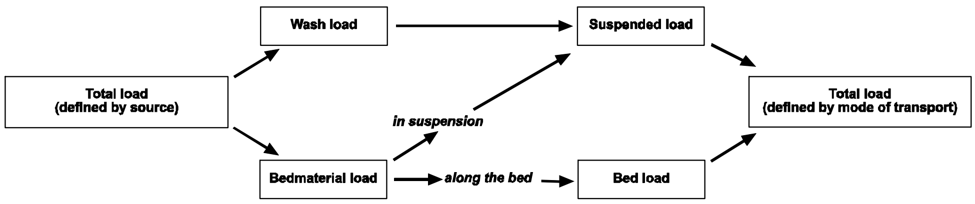

Figure 1.1: The total sediment load of a river can be divided into fractions depending on the primary mode of transport.

2. In terms of its source, the rest of the load can be divided into:

   a. Wash load - that part of the sediment load which consists of grain sizes that cannot easily be seen on the bed (Shen and Julien,1993). Essentially wash load is the material which stays in suspension all the time. That is, the material is floated rather than hydraulically pushed. Therefore wash load, like solution load, is not controlled by stream power. Wash load is often defined as that material which is smaller than fine sand (<0.062mm) i.e., silt and clay (Hicks and Griffiths, 1992).

   b. Bed material load - that part of the sediment load which consists of grain sizes represented on the bed (Shen and Julien,1993). This is usually interpreted to mean all the material which moves that is coarser than 0.062mm (Hicks and Griffiths, 1992). However, this definition assumes the river is not supply constrained. The alluvial nature of the Hutt flood plains means that it is not likely to be supply constrained.

Alternatively, that load which is not dissolved load can be divided in terms of its mode of transport into:

   a. Suspended load – all the material which is held in the flowing water by turbulence and moves at basically the same rate as the water. Suspended load contains some wash load and some bed material load. The major problem arises in determining whether material is bed material load or not. For example, there are times when particles move for a period in suspension and then drop back onto the bed.

   b. Bedload - is the material which predominantly stays on the bed during motion. This is the material which is hydraulically pushed and thus its movement requires stream energy. Bedload is not the same as bed material load. Bedload is the material which rolls, saltates (hops), and slides along the bed of the river. Bed material load is bedload but also includes material which is sometimes in suspension and sometimes on the bed e.g., sand particles.

The distinction between the modes of transport is rather arbitrary with material moving from one mode to the other as a function of available energy. Bedload transport is a function of energy; both the energy necessary to entrain particles, and the energy necessary to transport them. It is often therefore assumed that the rate of bedload movement is a function of the transport capacity of the flow (transport limited conditions). However, in many situations the actual transport rate is also a function of the availability of material (supply limited).

In summary, the sediment load is all the inorganic material which is transported by the flowing water i.e., boulders, sand, silt, clay, etc.

1.2 Flow/energy and sediment transport

Although properties other than size influence particle mobility (e.g., particle density and shape, degree of packing) size is often used as a convenient measure from which to estimate likely entrainment thresholds. Sundborg (1956) has determined these thresholds to be a function of flow velocity, distance from the bed, particle size, and specific gravity (Figure 1.2).

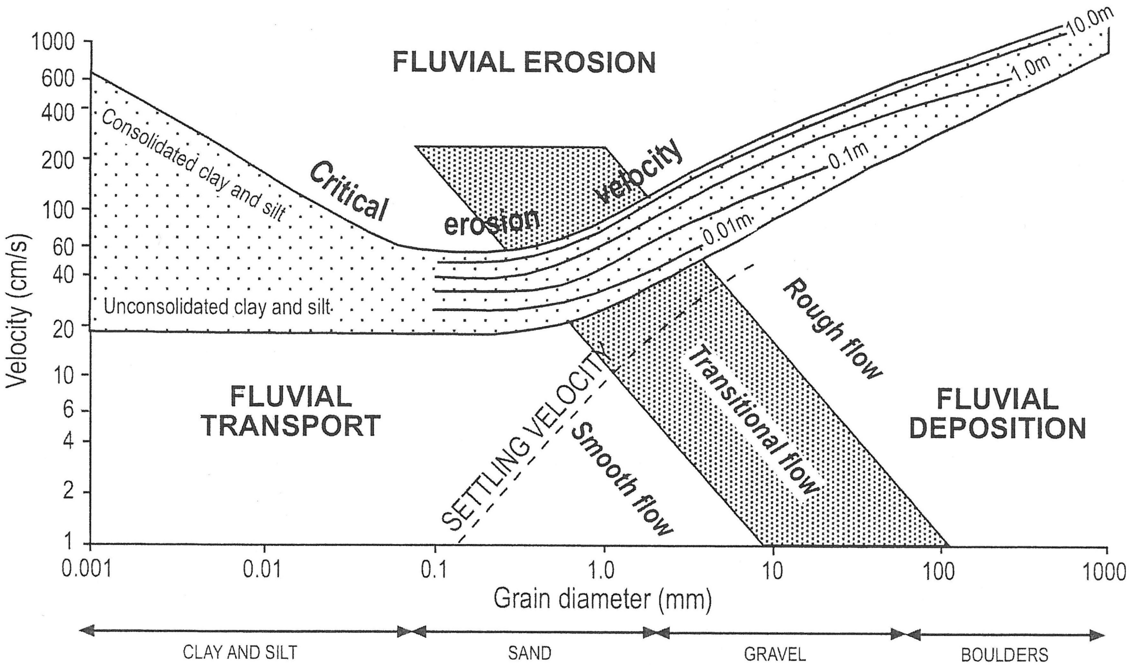

Figure 1.2: Erosion, entrainment, and transport thresholds for different size particles (After Sundborg, 1956).

Because velocity varies with distance from the river bed, and because in the ideal situation mean velocity occurs at a depth equal to a constant fraction of the total water depth, it is necessary to specify both the mean velocity and the depth at which it occurs. For example, assuming the theoretical velocity profile where velocity increases logarithmically from the bed until just below the water surface, a deeper flow will have a larger velocity at a constant fraction of the total water depth. It is important to note that because the electro-chemical forces that bind cohesive material together cannot be uniquely expressed as some function of particle size, the entrainment threshold boundaries for cohesive sediments are not exact. In addition, secondary flows and/or local turbulence may cause loose, unconsolidated clay or silt to be entrained at mean flow velocities lower than the boundary values indicate. Finally, in shallow water, such as close to the banks, velocity profiles do not vary as a simple function of depth as suggested above.

Entrainment thresholds are commonly defined for the median size (D_{50}) of bed and bank material. It is possible, however, that coarser material (either individual particles or aggregates) may form a protective armouring layer e.g., where failed material is deposited at the base or toe of the bank, or over time as a result of the winnowing of finer material. It is therefore useful to estimate entrainment velocities for the D_{90} grain size (the coarsest 10% of material sampled). It is also important to note that although intermediate particle sizes (i.e., fine sand or coarse silt) are generally considered the easiest to entrain (Knighton, 1998) smaller particles, once entrained, remain in suspension much longer because of their low depositional threshold.

1.3 Fluvial form and process

The interaction of stream flow with the landscape, and the erosion and transport of material as discussed above, tends to produce distinctive changes down a river profile. In general, the processes are characterised by the erosion and transport of the material from the upper catchment, conveyance through the mid reaches, and deposition within the lower channel or at the river mouth (Figure 1.3). This same sequence of processes is apparent within the Hutt catchment.

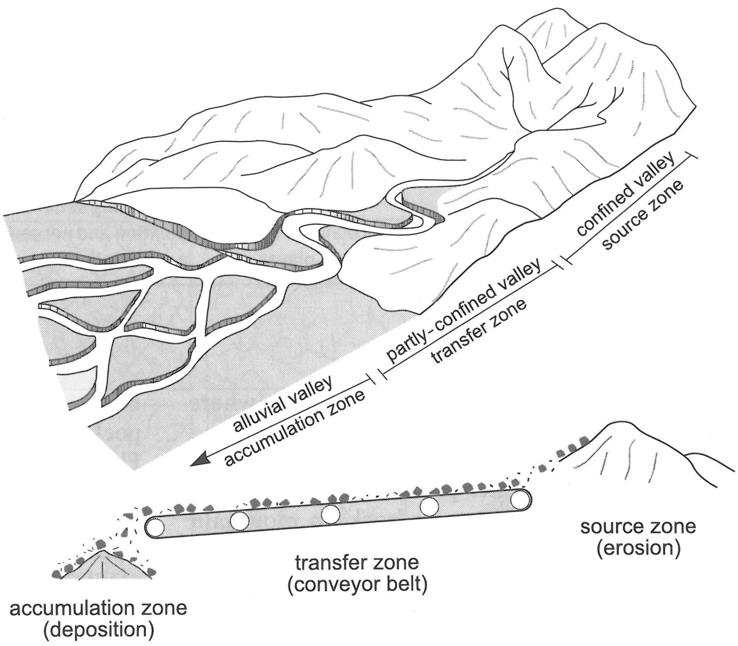

Figure 1.3: Characteristic erosion and sediment transport processes down a river profile (Brierley & Fryirs, 2005).

All these processes tend to operate only during flood conditions when there is sufficient energy to erode and transport the material. It is likely that only dissolved load is transported for the rest of the time.

The relationship between stream power and sediment transport, and the fluvial features that are formed as a consequence, can also be seen in the change in the character of the river from its headwaters to mouth (Figure 1.4).

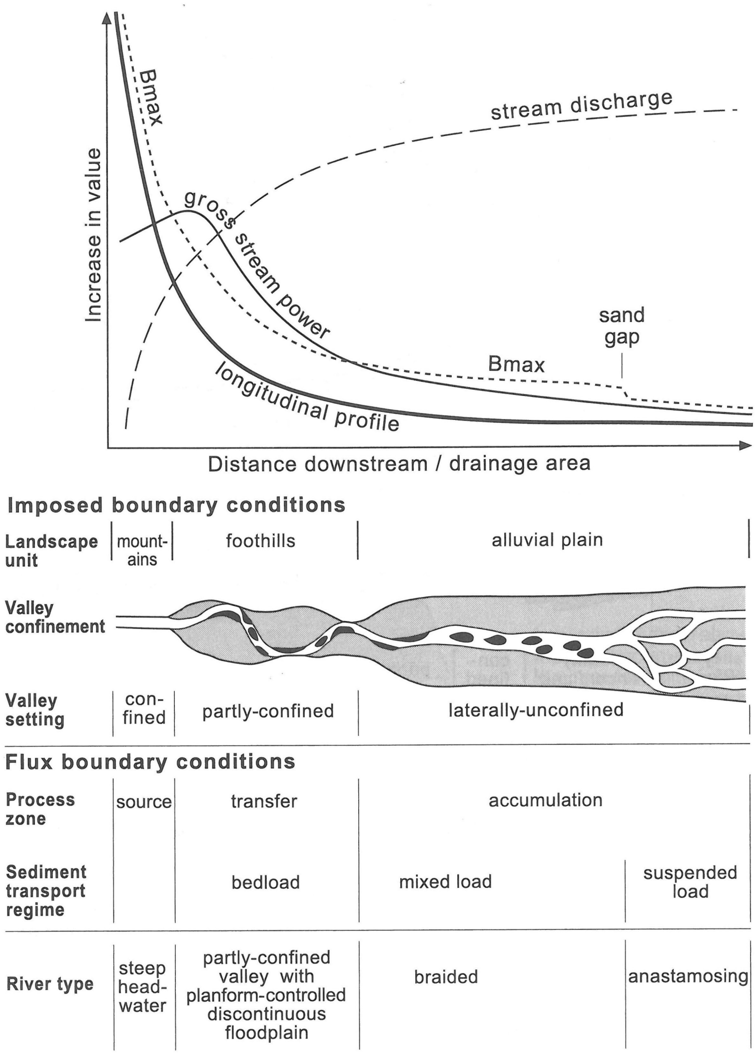

Figure 1.4: Changes in sediment and river character from the headwaters to the mouth (Brierley & Fryirs, 2005).

It can be seen that the total stream discharge (volume) increases downstream but gross stream power does not. This is because, while the amount of water increases down the catchment, the slope tends to decrease. This leads to a reduction in both the size and amount of sediment transported downstream. This variation in stream power down the river also helps to explain why the bed tends to degradate (i.e., erode) in its upper reaches and aggrade (i.e., build up) further down. This pattern of channel behaviour in the Hutt River was discussed in Opus (2010a).

The steep nature of the Hutt River explains why all the 'elements' and 'conditions' illustrated in Figure 1.4 are not found within the catchment, particularly those features related to a low gradient, fine sediment, system.

Of importance to this discussion of the sediment transport processes of the Hutt River are the relationships between sediment size, material transport volume, channel slope, and discharge (Figure 1.5). An decrease in channel slope will result in both decrease in the size and amount of sediment transported i.e., aggradation. Likewise, an increase in discharge will result in the erosion and transport of larger, and more, material. Fundamental to understanding the sediment transport regime is therefore knowledge of the flow regime, and how this varies over time.

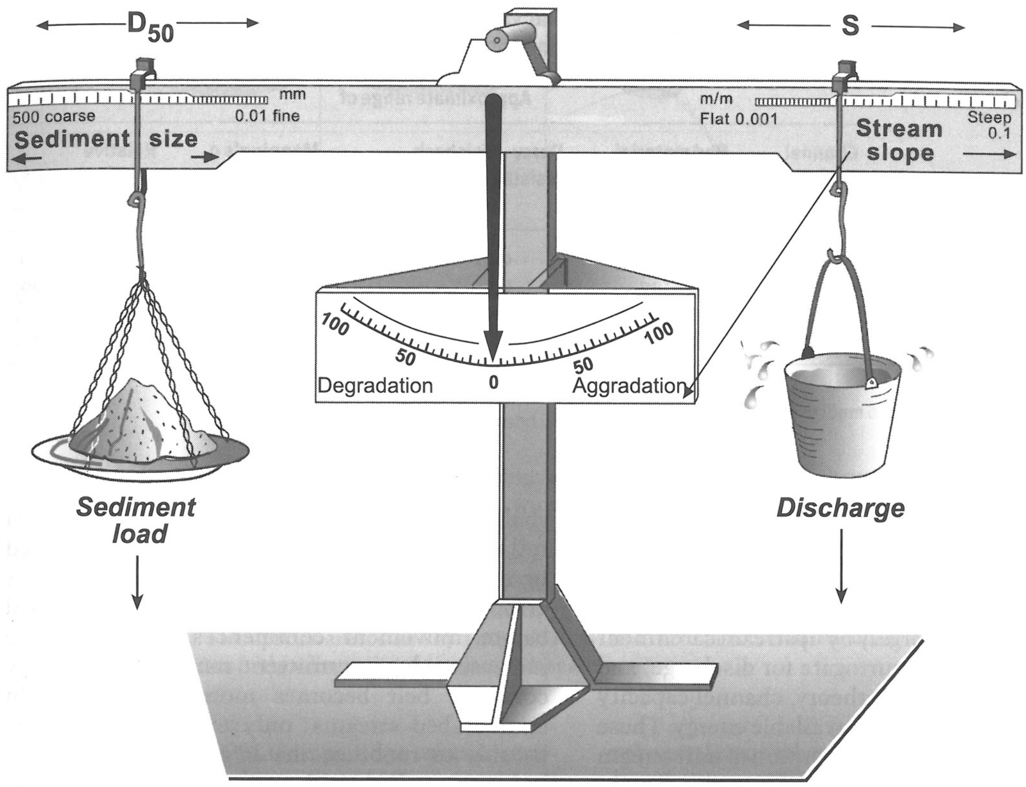

Figure 1.5: Changes in sediment and river character from the headwaters to the mouth (Brierley & Fryirs, 2005).

1.4 Previous and additional 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 of the Hutt River system, the natural conditions of the main channel and the channel changes that have taken place since European colonisation, the form of the natural meander patterns and their use in defining appropriate design channels, the channel resistance, and the variations in channel geometry); and provides a sedimentation study (i.e., an estimation of bed material transport rates and hence transport rating curves, the calculation of bed material movement from the rating curves, and an assessment of the transport balance given estimated channel changes and the extraction of material from the channel bed).

The suspended sediment transport rating curves calculated by Williams (1991) have been used in this current report to estimate the volume of suspended sediment transported down the Hutt River between 1987 and 2009. Results from Williams (1991) have also been used to calibrate the results of the present bedload transport study.

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. Cross-sectional data, and a hydrographic survey of the sea-floor at the river mouth, are used to monitor bed movement and the impact of gravel extraction. Volume changes calculated in Gardner (2010) were used to calibrate the results of bedload and suspended sediment calculations in this report.

The current report is intended to be read in conjunction with two additional reports:

- Hutt River Mouth: Sediment inputs and aggradation of the lower part of the Hutt River (Opus 2010a); and
- Hutt River Mouth: Coastal sediment transport processes and beach dynamics (Opus, 2010b).

1.5 Hydraulic significance of Taita Gorge

As covered in a supplementary report (Opus, 2010a) a control volume for the sediment analyses has been defined. The downstream boundary of this volume is the Hutt River mouth, and the upstream boundary is at cross-section 980. This cross-section is approximately 39.7km upstream of the river mouth; it is also the closest cross section to the Taita Gorge flow gauging station. Further, this site is at the upstream limit of the modelled backwater profile during extreme flood events. All calculations for bedload and suspended load transport have therefore been undertaken relative to cross-section 980. There are no significant inflows of either water or sediment downstream of this location.

2 Flow regime of the Hutt River at Taita Gorge

2.1 Introduction

The critical control of streamflow on erosion and sediment transport makes it is important to have a good understanding of the flow (or hydrologic) regime of the Hutt River. The most downstream flow gauging station on the Hutt River is at Taita Gorge. This site, as explained already, is below the last tributary providing significant inputs of water and sediment to the river. Measurements at this site therefore provide a good estimate of the flow in the lower river.

Flows have been measured at Taita Gorge since 1979 (Figure 2.1). There are a number of relatively small gaps in the flow record, however, it provides a reliable basis upon which to assess variability of the flow regime of the lower Hutt River.

The highly variable flow regime is typical of a river draining a hill-country catchment. There are occasional large floods events 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 (Table 2.1). Over the past 31 years flows in the Hutt River have varied from as low as 1.6m³/s to approximately 1562m³/s (Figure 2.1 & Table 2.1).

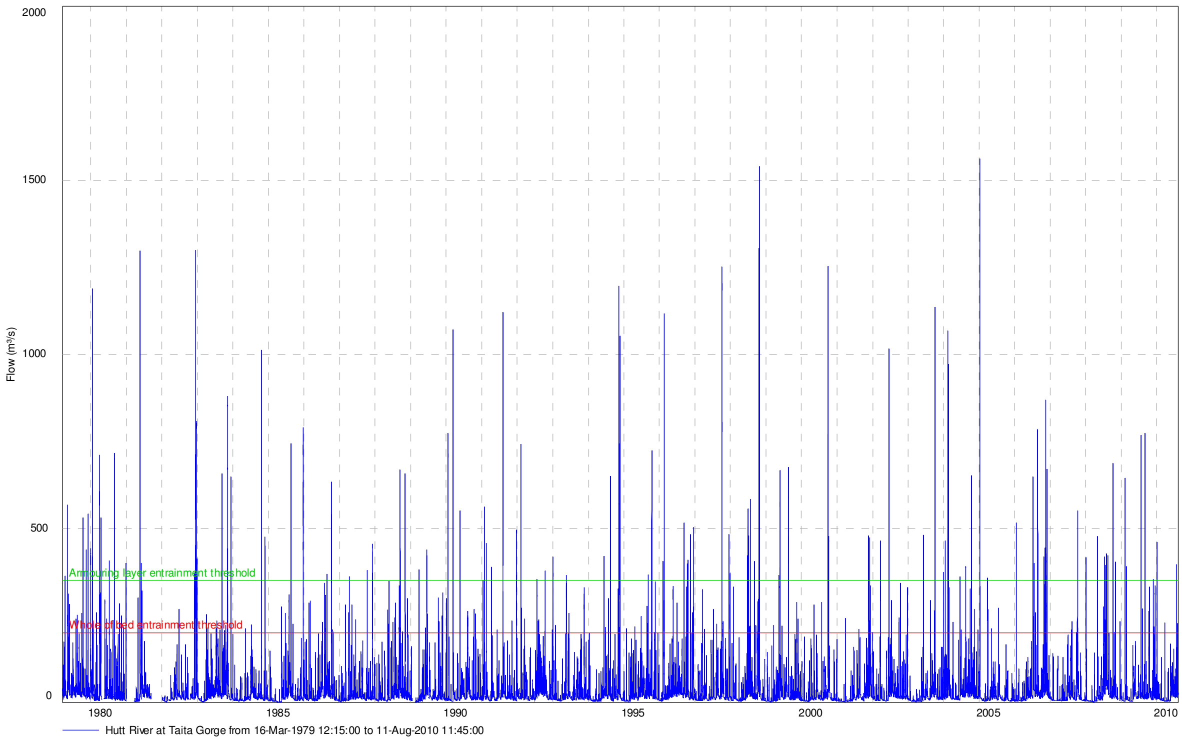

Figure 2.1: Flow record for the Hutt River at Taita Gorge, including two bedload entrainment thresholds (1979-2010).

Table 2.1: Statistical summary of flow record at Taita Gorge 1979-2010 (m³/s).

Minimum	Mean	Maximum	Standard deviation	Lower quartile	Median	Upper quartile
1.6	24.8	1562	44.5	8.1	14.2	25.7

Flow regimes are perhaps most simply summarised by a flow-duration curve, a cumulative frequency plot of flow (Figure 2.2). Such plots show the proportion of time during which flow is equal to or greater than given magnitudes, regardless of chronological order. The overall slope of the flow-duration curve indicates the flow variability. Because of the large range of flows experienced within the Hutt River, and therefore the relatively poor resolution at both ends of the distribution, the flow-duration data can be summarised in tabular form (Table 2.2).

According to Williams (1991) the average flow threshold for bedload transport for the lower valley, when considering just the armouring layer, is approximately 350m³/s. When the characteristics of the sediment forming the entire bed are considered the entrainment threshold reduces to 200m³/s. This shows the increased resistance of the larger material forming the armouring layer. This layer 'protects' the finer material beneath. Therefore, there should be no bedload movement at flows below 200m³/s. These two entrainment thresholds are also shown on Figure 2.1 with reference to the flow record.

Over the entire flow record from Taita Gorge the upper entrainment threshold has been exceeded 0.3% of the time; the lower threshold 0.8% of the time. Notwithstanding these relatively low percentages, the large amount of available energy during these periods is sufficient to erode and transport a significant volume of material.

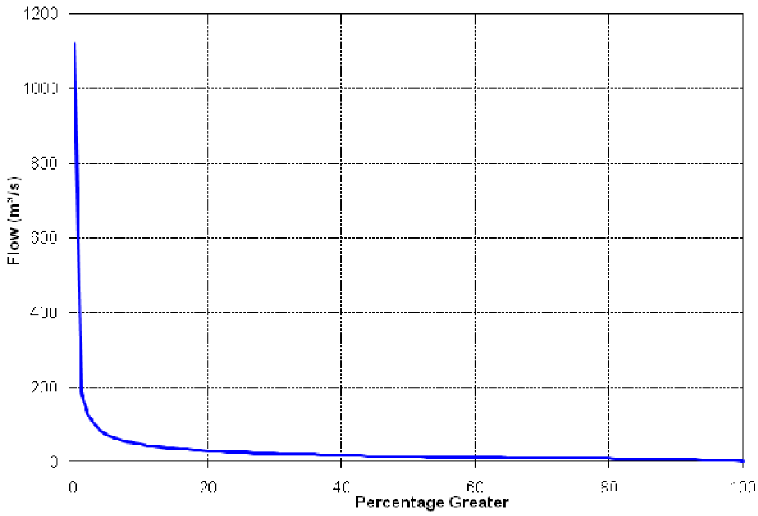

Figure 2.2: Flow distribution for the Hutt River at Taita Gorge (1979-2010).

Table 2.2: Distribution of the instantaneous flows (m³/s) in the Hutt River (1979-2010).

	0	1	2	3	4	5	6	7	8	9
0	1562.3	187.6	131.3	103.6	86.2	75.0	66.5	60.1	55.0	50.9
10	47.6	44.8	42.2	40.0	38.1	36.3	34.7	33.3	32.0	30.9
20	29.8	28.9	28.0	27.2	26.5	25.7	25.0	24.3	23.7	23.1
30	22.5	21.9	21.4	20.9	20.4	19.9	19.4	18.9	18.5	18.0
40	17.6	17.3	16.9	16.5	16.2	15.8	15.5	15.2	14.9	14.6
50	14.2	13.9	13.7	13.4	13.1	12.8	12.5	12.2	12.0	11.7
60	11.5	11.2	11.0	10.7	10.5	10.3	10.1	9.8	9.6	9.4
70	9.2	9.0	8.7	8.5	8.3	8.1	7.9	7.7	7.4	7.2
80	7.0	6.8	6.6	6.3	6.1	5.9	5.7	5.5	5.3	5.1
90	4.9	4.7	4.5	4.3	4.1	3.8	3.5	3.2	2.9	2.4
100	1.6									

2.2 Velocity and sediment transport

As outlined earlier, there is a strong relationship between flow velocity and the size of material that can be eroded and transported (Figure 1.2). It is therefore important to understand the relationship between flow and velocity, and consequently the size of material that can be eroded and transported under different conditions.

The flow gauging data related to the Taita Gorge site were used to develop a relationship between flow and average velocity (Figure 2.3). While it is likely that the maximum velocity is actually more critical to particle erosion and transport, these data are not available. The use of the mean velocity will produce a conservative estimate of the maximum particle size likely to be transported at a given flow.

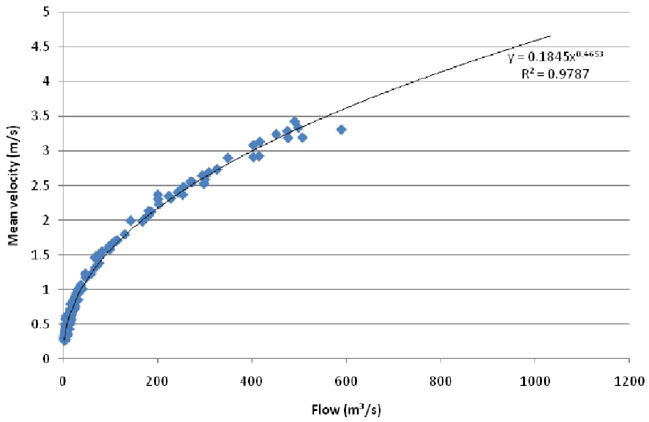

Figure 2.3: Relationship between flow and mean velocity for the Hutt River at Taita Gorge.

The use of the mean velocity of given flows at Taita Gorge, together with Figure 1.2, allows an estimation of the likely maximum particle size able to be transported under particular conditions (Table 2.3). This relationship assumes a specific density of the particles of 2.65. This value is consistent with the specific density of quartz and feldspar, the predominant minerals in greywacke which forms the bulk of sediment within the Hutt River.

Table 2.3: Maximum size of sediment 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

From Table 2.3 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 200m^3/s the mean velocity at Taita Gorge is 2.2m/s. Flows of this magnitude can theoretically transport particles up to about 75mm in diameter. At flows of 1600m^3/s, approximately the largest flow recorded at Taita Gorge, the mean velocity is 5.7m/s and particles up to 500mm in diameter can be moved.

2.3 Inter-survey periods

The Greater Wellington Regional Council (GWRC) regularly surveys cross-sections at 313 locations along the lower 33.5km of the Hutt River. The data from these surveys are used to analyse trends in gravel bed material movement, and bed aggradation and degradation along the river. The results of this analysis are the used as a basis for determining policy on gravel extraction and general river management.

The last five surveys were carried out in 1987, 1993, 1998, 2004, and 2009. Given the number of river cross-sections to be surveyed, each survey took several months to complete. Table 2.4 notes the period of each survey that has been assumed for the purposes undertaking the analysis in this report, and the companion report on sediment input and aggradation in the lower river (Opus, 2010a).

Table 2.4: Assumed survey dates.

Survey year	Survey period	Assumed survey end date
1987-1989	May-September 1987 (mouth to Silverstream Bridges) October to December 1988 (Silverstream Bridges to Birchville Gorge) August to September 1989 (Birchville Gorge to Hutt Gorge)	1 Sept1987
1993	April-August 1993	1 August 1993
1998	January-April 1998	1 April 1998
2004	December 2003-April 2004	1 April 2004
2009	September 2008-April 2009	1 April 2009

To calibrate the bedload and suspended sediment transport rates derived in the current report it is necessary to use these same four inter-survey periods.

2.4 Inter-survey flow variability

The variability of flow in the Hutt River over time, and the control of flow on sediment transport, means that sediment transport will also vary over time. To allow valid calibration and comparison of the calculated sediment transport rates with the aggradation that occurred over the lower river, comparable time periods must be used. Flow variability in the Hutt River over each inter-survey period was therefore summarised (Figure 2.4 to Figure 2.7 & Table 2.5 to Table 2.8).

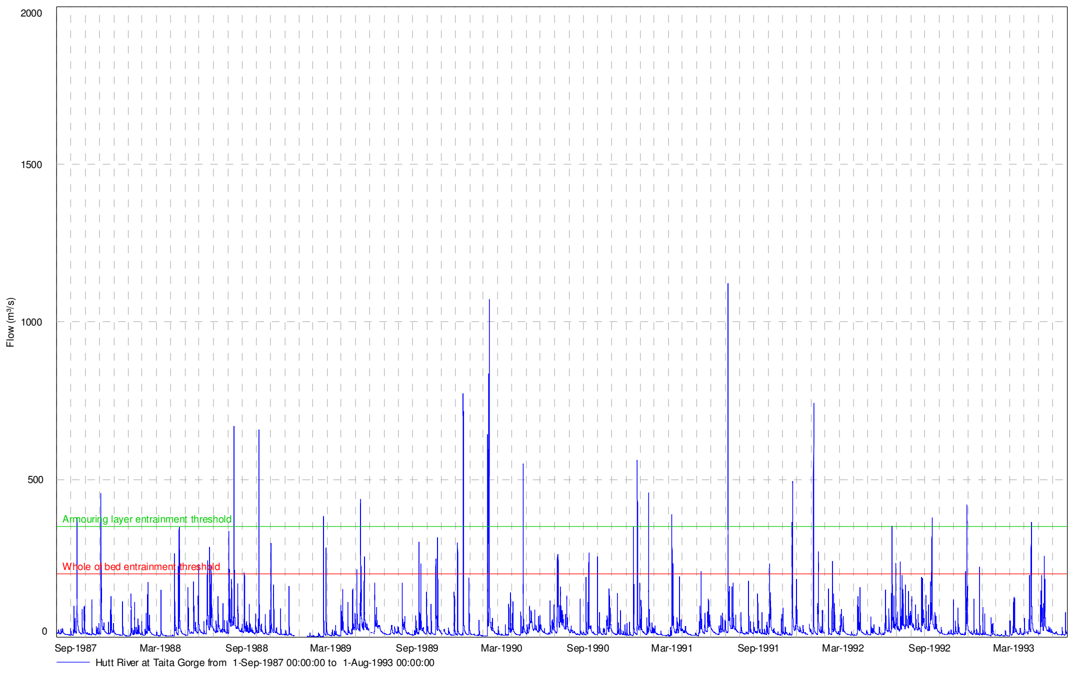

Figure 2.4: Flow record for Hutt River at Taita Gorge 1 Sept 1987-31 July 1993, including bedload entrainment thresholds.

Table 2.5: Distribution of the instantaneous flows (m^3/s) in the Hutt River (1987-1993).

	0	1	2	3	4	5	6	7	8	9
0	1121.6	184.4	128.5	100.6	83.8	72.8	64.6	58.3	53.2	49.3
10	46.1	43.1	40.7	38.6	36.9	35.4	34.0	32.6	31.4	30.3
20	29.2	28.3	27.5	26.7	25.9	25.3	24.6	23.9	23.3	22.7
30	22.1	21.6	21.0	20.5	20.0	19.5	19.0	18.5	18.1	17.7
40	17.3	17.0	16.6	16.3	15.9	15.6	15.3	15.0	14.8	14.5
50	14.2	14.0	13.7	13.5	13.2	13.0	12.7	12.5	12.2	12.0
60	11.8	11.6	11.3	11.1	10.9	10.8	10.6	10.4	10.2	10.0
70	9.8	9.7	9.5	9.3	9.2	9.0	8.8	8.7	8.5	8.3
80	8.2	8.0	7.8	7.7	7.5	7.3	7.1	6.9	6.7	6.5
90	6.3	6.1	5.8	5.6	5.3	5.0	4.6	4.2	3.6	2.8
100	1.6									

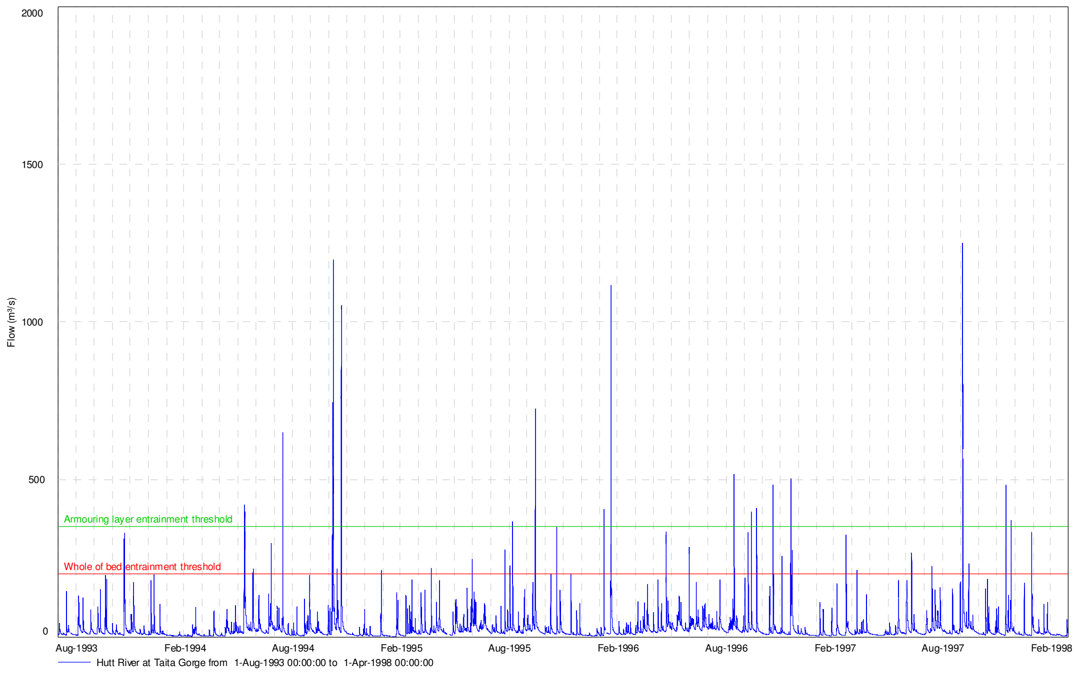

Figure 2.5: Flow record for Hutt River at Taita Gorge 1 August 1993-31 March 1998, including bedload entrainment thresholds.

Table 2.6: Distribution of the instantaneous flows (m³/s) in the Hutt River (1993-1998).

	0	1	2	3	4	5	6	7	8	9
0	1250.6	175.1	124.5	98.1	82.2	71.8	63.9	57.8	52.9	49.0
10	45.8	43.2	40.8	38.9	37.1	35.4	33.9	32.5	31.4	30.4
20	29.5	28.6	27.9	27.1	26.5	25.8	25.2	24.5	23.9	23.4
30	22.9	22.4	21.9	21.4	21.0	20.5	20.0	19.6	19.2	18.8
40	18.5	18.1	17.7	17.4	17.0	16.7	16.3	16.0	15.7	15.4
50	15.1	14.7	14.4	14.1	13.9	13.6	13.3	13.0	12.8	12.5
60	12.2	12.0	11.7	11.5	11.3	11.0	10.8	10.6	10.4	10.2
70	9.9	9.7	9.5	9.3	9.1	8.9	8.7	8.5	8.2	8.0
80	7.8	7.6	7.3	7.1	6.9	6.6	6.4	6.1	5.9	5.7
90	5.5	5.3	5.1	4.9	4.6	4.4	4.2	3.9	3.5	3.1
100	1.7									

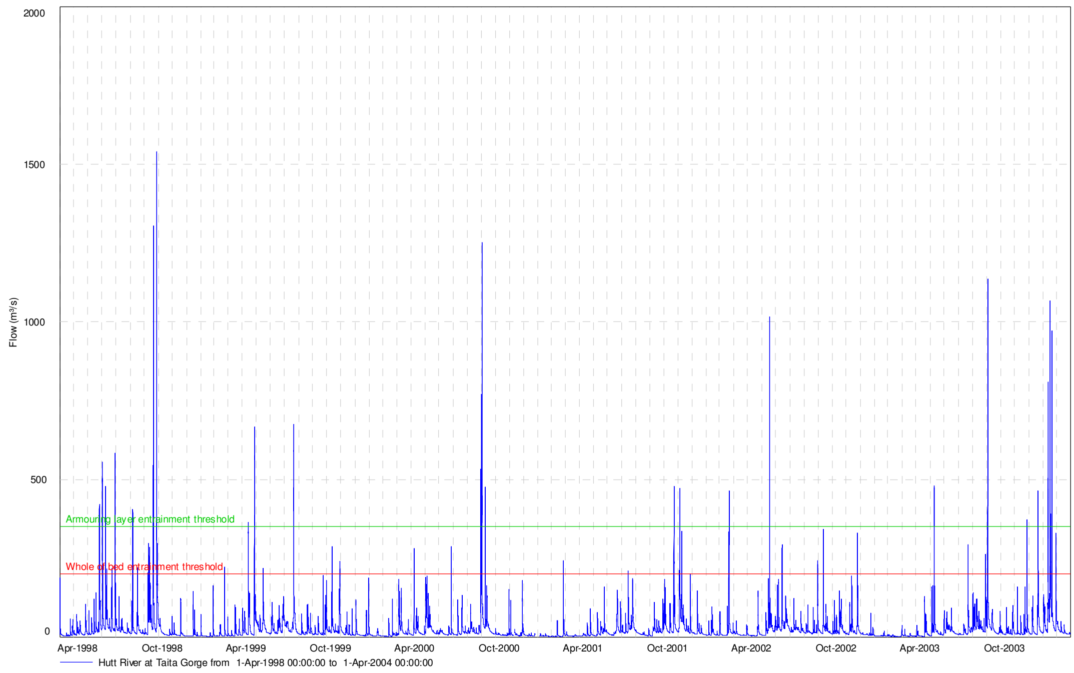

Figure 2.6: Flow record for Hutt River at Taita Gorge 1 April 1998-31 March 2004, including bedload entrainment thresholds.

Table 2.7: Distribution of the instantaneous flows (m³/s) in the Hutt River (1998-2004).

	0	1	2	3	4	5	6	7	8	9
0	1540.1	188.8	129.7	104.4	87.9	76.2	67.4	60.8	55.7	51.4
10	47.9	45.0	42.1	39.6	37.5	35.8	34.3	32.8	31.4	30.1
20	29.0	28.0	27.1	26.1	25.2	24.4	23.5	22.8	22.0	21.3
30	20.7	20.1	19.6	19.1	18.5	18.0	17.6	17.2	16.8	16.4
40	16.0	15.7	15.3	15.0	14.6	14.2	13.9	13.6	13.3	13.0
50	12.7	12.4	12.1	11.8	11.6	11.3	11.1	10.8	10.6	10.4
60	10.2	9.9	9.7	9.5	9.3	9.1	8.8	8.6	8.4	8.1
70	7.9	7.7	7.5	7.3	7.1	6.9	6.7	6.5	6.3	6.1
80	5.9	5.7	5.5	5.3	5.1	4.9	4.7	4.5	4.3	4.2
90	4.0	3.8	3.6	3.5	3.3	3.1	3.0	2.7	2.5	2.2
100	2.1									

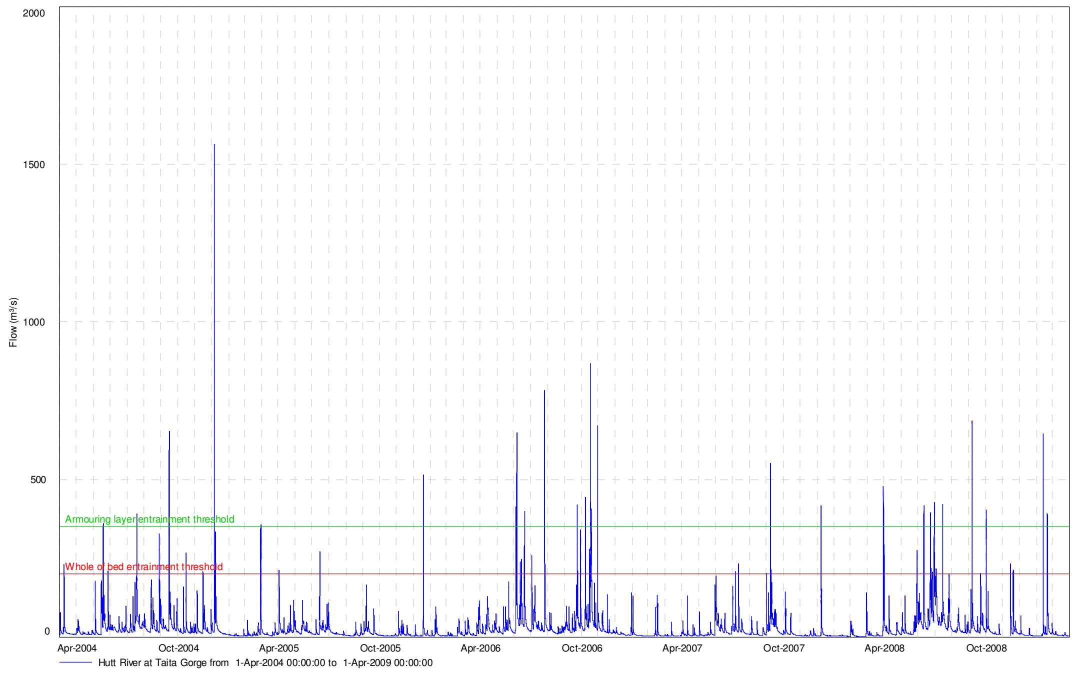

Figure 2.7: Flow record for Hutt River at Taita Gorge 1 April 2004-31 March 2009, including bedload entrainment thresholds.

Table 2.8: Distribution of the instantaneous flows (m³/s) in the Hutt River (2004-2009).

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	1562.3	198.4	138.0	106.0	88.0	76.6	68.1	61.8	56.8	52.6
10	49.1	46.4	43.8	41.5	39.4	37.6	35.8	34.2	32.7	31.5
20	30.4	29.4	28.4	27.5	26.7	25.8	25.0	24.3	23.6	22.9
30	22.3	21.7	21.1	20.5	20.0	19.6	19.1	18.6	18.2	17.7
40	17.3	16.9	16.5	16.1	15.7	15.3	15.0	14.5	14.1	13.7
50	13.4	13.0	12.6	12.3	12.0	11.6	11.3	11.0	10.7	10.4
60	10.1	9.9	9.6	9.4	9.1	8.9	8.7	8.5	8.3	8.0
70	7.8	7.6	7.3	7.1	6.9	6.6	6.4	6.2	6.0	5.9
80	5.7	5.5	5.4	5.2	5.0	4.9	4.8	4.7	4.6	4.5
90	4.4	4.3	4.2	4.1	4.0	3.8	3.6	3.4	3.1	2.6
100	2.3									

When comparing the flow regimes for the various inter-survey periods it is apparent that natural flow variability can have a significant effect on the amount of energy available to transport material. This is reflected in the number of flood events experienced, flood magnitude, and the time over which the flows are above the entrainment threshold. Some periods have more floods and spend more time above the entrainment threshold than others.

For example, the period from 1987-1993 had only a relatively few floods, and these were of relatively small magnitude. The period from 1998-2004 had a number of large flood events, including the largest flood recorded over the entire length of record.

It should also be noted that stream power, and therefore the amount of energy available to erode and transport material, is not a simple linear function of flow. The amount of energy, and consequently both the amount of material and its size, increase geometrically with flow. Consequently, larger flood events carry a 'disproportionate' amount of material. A single very large flood event can erode and transport a significant amount of material, potentially the majority of material over any inter-survey period.

The flow, and therefore energy, variability over each of the inter-survey periods is summarised in Table 2.9 and Figure 2.8. The percentage of time that flow was above the two entrainment thresholds defined by Williams (1991) in each inter-survey period is presented in Table 2.10.

Table 2.9: Statistical summary of flow record at Taita Gorge (m^3/s) for each inter-survey period.

Measurement	1987-1993	1993-1998	1998-2004	2004-2009	1979-2010
Minimum	1.6	1.7	2.1	2.3	1.6
Maximum	1121.6	1250.6	1540.1	1562.3	1562.3
Mean	24.5	24.8	24.1	24.6	24.8
Std deviation	40.5	44.3	48.8	43.7	44.5
Lower quartile	9.0	8.9	6.9	6.6	8.1
Median	14.2	15.0	12.7	13.3	14.2
Upper quartile	25.3	25.8	24.4	25.8	25.7

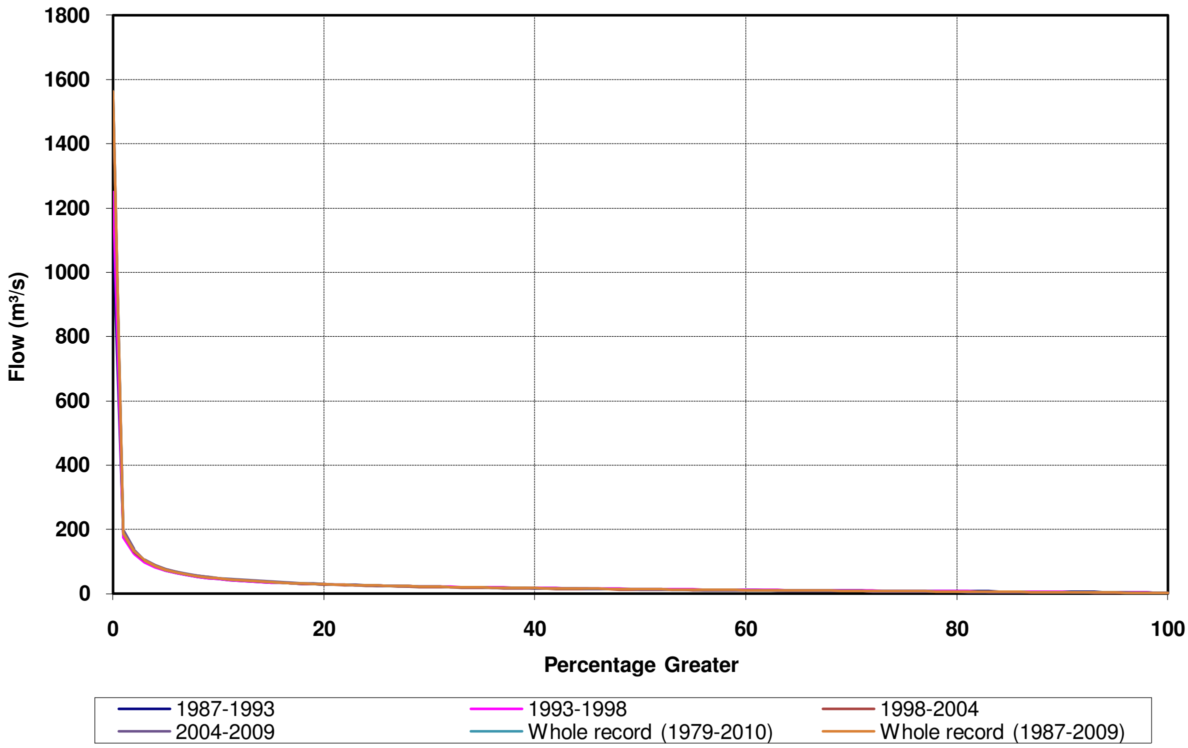

Figure 2.8: Flow distribution over each inter-survey period.

Table 2.10: Percentage of time over each inter-survey period that flow was greater than the entrainment thresholds defined by Williams (1991).

	200m³/s (%)	350m³/s (%)
1987-1993	0.8	0.3
1993-1998	0.8	0.25
1998-2004	0.75	0.3
2004-2009	0.9	0.4
1981-2010	1.0	0.5

2.5 Flow distribution curves used for calculations

A standard flow distribution curve was initially calculated for use in the bedload transport equations for each inter-survey period. However, a second flow distribution curve was subsequently calculated which included increased resolution at high flows (Table 2.11).

The impact of the 'increased sensitivity curve' to the bedload transport estimates is significant. This is because of the nature of the relationship between flow and sediment transport as discussed earlier. This is further discussed in Section 4.3. The 'increased sensitivity curves' for each period are considered to produce the more accurate results, because of the effect of high flows on sediment transport, and so have been used in subsequent analysis.

Table 2.11: Flow distributions (1987-1993).

Exceedance probability (%)	Standard distribution	Increased high flow sensitivity
100	1.63	1.63
90	6.28	6.28
80	8.19	8.19
70	9.83	9.83
60	11.76	11.76
50	14.21	14.21
45	15.61	15.61
40	17.31	17.31
35	19.51	19.51
30	22.13	22.13
25	25.30	25.30
20	29.23	29.23
15	35.36	35.36
10	46.10	46.10
9	49.27	49.27
8	53.24	53.24
7	58.25	58.25
6	64.64	64.64
5	72.77	72.77
4	83.76	83.76
3	100.58	100.58
2	128.49	128.49
1	184.40	184.40
0.9		190.88
0.8		203.27
0.7		215.59
0.6		231.60
0.5		250.12
0.4		282.16
0.3		324.77
0.2		376.83
0.1		496.38
0	1121.57	1121.57

3 Bed and bank material

There is limited data available with regard to bed and bank sediment characterisation in the vicinity of Taita Gorge. Williams (1991) produced sediment size distribution curves for cross-sections 720 and 1120 (among others) for both the armouring layer, and the whole of the bed. These have therefore been used to generate an estimated sediment distribution curve for Taita Gorge (cross-section 980).

Initially, the cross-section 980 armouring layer sediment size distribution was estimated by drawing an average curve between the two curves provided for cross-sections 720 and 1120 in Williams (1991). However, after further consideration a composite curve was developed using the average of cross-sections 720 and 1120 for the smaller particles sizes (up to

100mm), and the results from cross-section 720 for the larger particle sizes. This composite curve is considered to be a good representation of the bed material over the control reach at Taita Gorge. The resulting sediment distribution curves for the armouring layer are listed in Table 3.1. The particle size distribution curve for the whole of the bed material from cross-section 720 was considered to be representative of Taita Gorge. These data are also listed in Table 3.1.

Table 3.1: Sediment distribution curves.

	Armouring layer		Whole of bed
	Average of cross-sections 720 & 1120	Average of cross-sections 720 & 1120 up to 100mm; cross-section 720 used for >100mm	Cross-section 720
Particle size (mm)	Percentage smaller than		
256	100	100	100
180	75	89	95.5
128	60	73	89
90	46	46	75
64	35	35	62
45	27.5	27.5	51.5
32	24	24	44
22	18.5	18.5	36
16	17	17	32
11.2	12.5	12.5	27.5
8	9.5	9.5	23.5
5.6	7	7	20
4	6.5	6.5	16
2	4	4	10
1	2	2	6.5
0.25	0	0	2
0.125			0

4 Bedload

Since bedload is the material that is hydraulically rolled, slid, or pushed, transport of bedload requires stream energy.

Problems associated with direct measurement of bedload provided the impetus for the derivation of theoretical formulae. Theoretical formulae are based on the assumption that the dynamics of particle motion can be used to predict bedload movement. If streams were 100% efficient, then transport and erosion would be fully explained by stream power, or its surrogate, velocity. However, 95-97% of stream power is expended by intra-fluid friction and therefore not used to undertake work. Nevertheless, in non-supply limited situations, such as the Hutt River, the amount of bedload transported is limited by stream power and the force it has to overcome against bed material. Thus, the main bedload transport equations rely on stream power, excess shear force, and discharge.

4.1 Bedload transport equations

BAGS (Bedload Assessment for Gravel-bed Streams) is sediment transport modelling software developed by Rocky Mountain Research Station, Forest Service, USDA. It has been used to calculate bedload transport rates, and consequently volumes, for the control reach between the river mouth and Taita Gorge (cross-section 980). Transport capacities are calculated on the basis of field measurements of channel geometry, average reach slope, and the bed material grain size. BAGS is now regarded as one of the 'industry standards' with regard to bedload transport modelling.

Four of the six available bedload transport equations, developed specifically for gravel-bed rivers, were used to estimate bedload transport down the Hutt River past Taita Gorge:

- The surface-based equation of Parker (1990)
- The surface-based equation of Wilcock and Crowe (2003)
- The substrate-based equation of Parker, Klingeman and McLean (1982)
- The substrate-based equation of Parker and Klingeman (1982)

BAGS outputs several variables, in a table format, including the average bedload transport rate (which can be converted to a bedload transport volume) and a water depth for the various discharges provided in the flow distribution.

To compare the various sediment transport equations, constant values for each variable were used in BAGS, including a synthetic flow distribution curve. The resulting bedload transport rates (converted to tonnes per day) have been graphed against discharge to produce a bedload transport rating curve (Figure 4.1). The equivalent curves for each of the three equations used by Williams (1991) have also been plotted, these are:

- Meyer-Peter and Muller
- Engelund-Hansen
- Einstein-Brown

Figure 4.1 shows that each of the equations used by Williams (1991) predicts higher bedload transport rates than any of the equations from BAGS. During very large flood events, the Einstein-Brown equation produces similar results to the substrate-based BAGS equations. The Wilcock and Crowe equation always produces higher bedload transport rates than the Parker equation. The results of the two substrate-based equations are similar. At lower flows (up to ~700m^3/s), the substrate-based equations produce lower bedload transport rates than both of the surface-based equations. However, at flows greater than ~1000m^3/s, the substrate-based equations produce higher bedload rates than both of the surface-based equations.

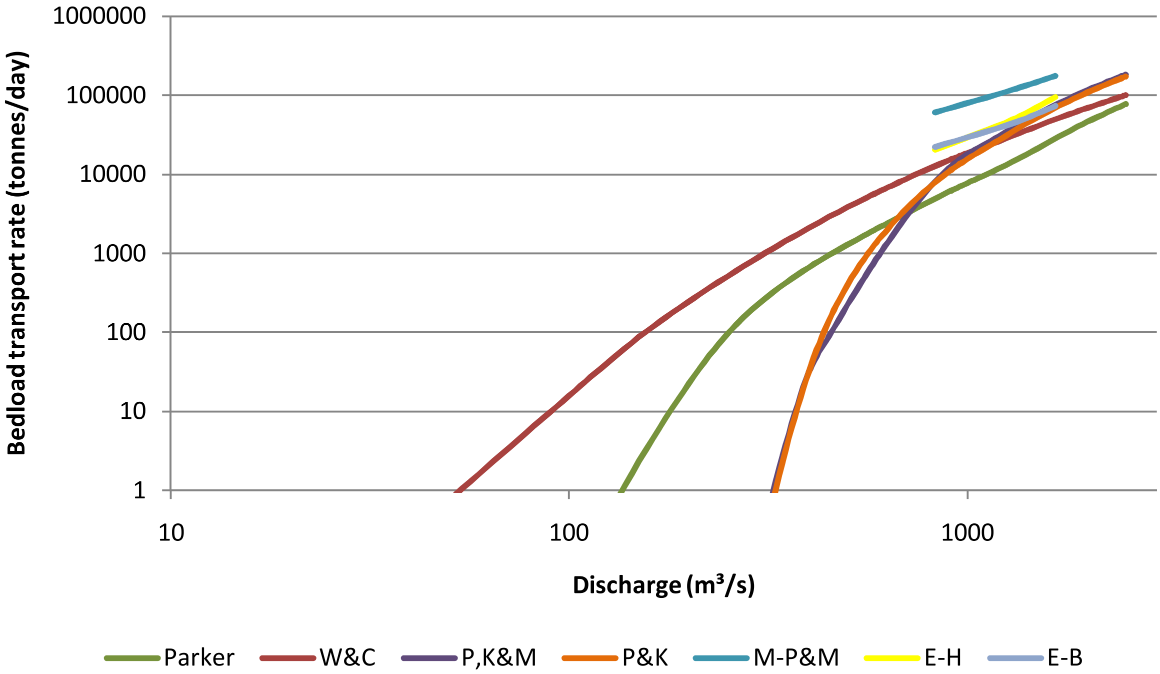

Figure 4.1: Bedload transport rating curves.

4.2 Calibration

The water depths produced by BAGS were used as a calibration check by comparing the results to those from a MIKE11 hydraulic model of the Hutt River. For the 1987-1993 inter-survey period, the results from both Parker and Wilcock & Crowe were converted to a flow rating curve and then plotted against the MIKE11 results (Figure 4.2). The two sets of results are very similar. This indicates that BAGS is interpreting the cross-section data appropriately.

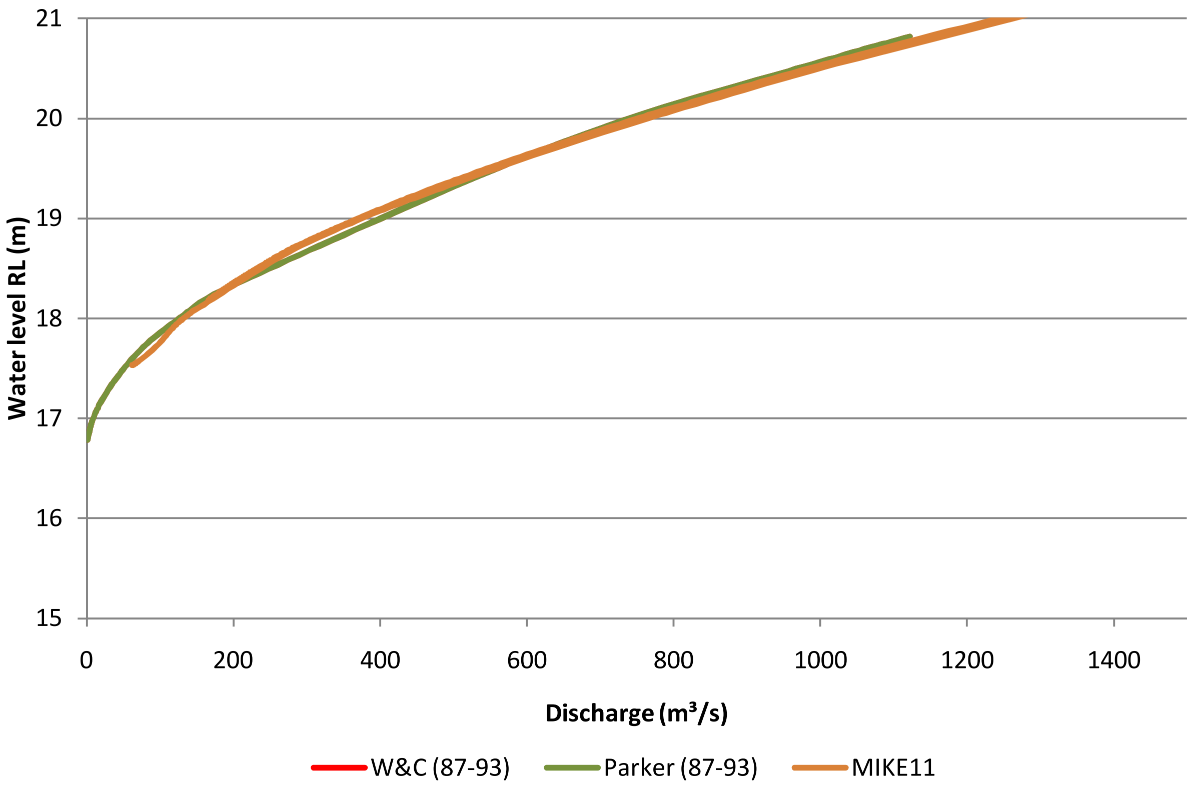

Figure 4.2: Modelled discharge/water level rating curves.

4.3 Sensitivity of the bedload modelling

To test the sensitivity of the BAGS equations to different input variables the analysis was repeated several times, adjusting only one parameter at a time. The results of adjusting the sediment grading curve for the larger particle sizes (>100mm) show that there are only small differences in estimated bedload transport (Figure 4.3).

The results of adjusting the sensitivity of the flow distribution for high flow events show that there is a large difference in the estimate of the volume of bedload transported (Figure 4.4). This is a consequence of the geometric relationship between flow and sediment transport discussed earlier. While the majority of the sediment is moved during high flow events, the amount and size of material transported are very sensitive to variations in flow, particularly flow velocity. Because of the nature of the relationship between flow and sediment transport shown in Figure 1.2, small changes in flow can result in big changes in sediment transport. Providing greater sensitivity to the high flow distribution allows the exponential nature of the flow distribution to be better modelled. This has the effect of generally reducing the magnitude of flows over most of the top end of the distribution. This consequently reduced the estimate of the total amount of sediment being transported.

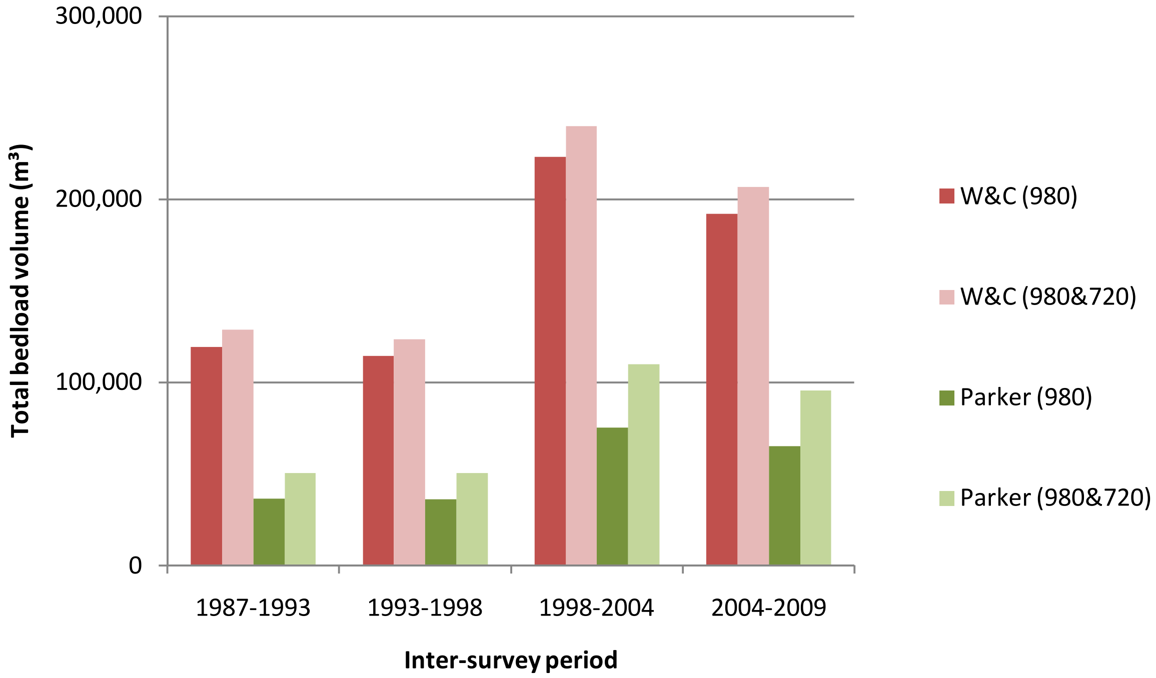

Figure 4.3: Effects of different sediment grading curves.

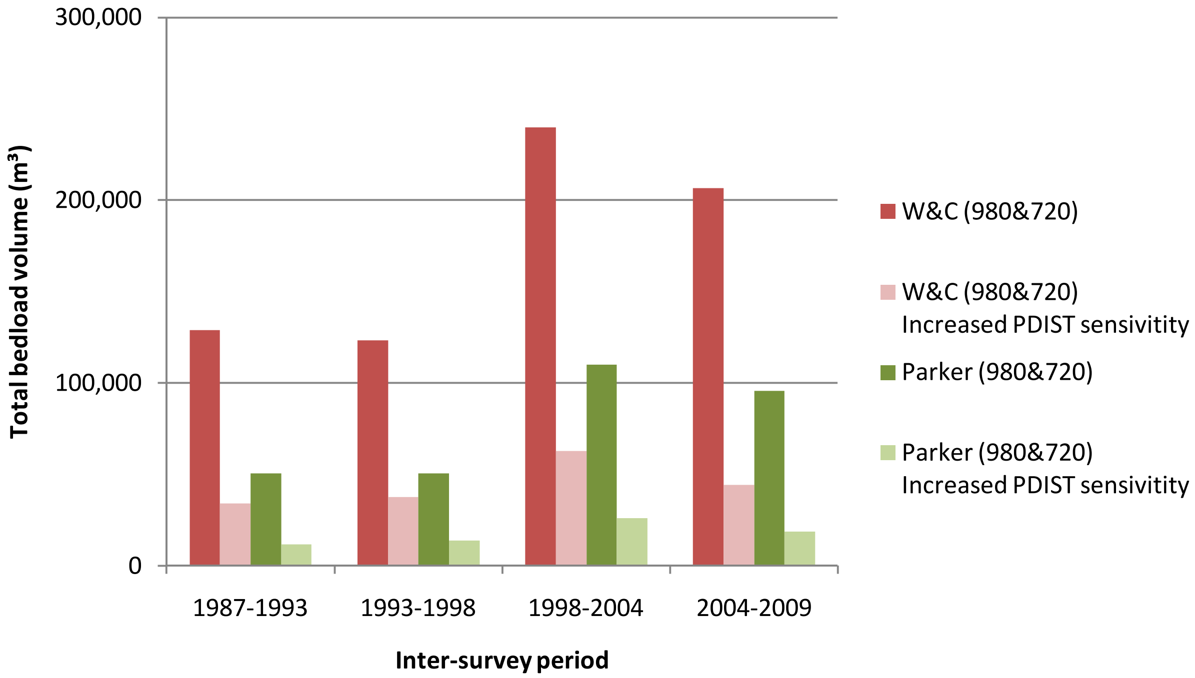

Figure 4.4: Effects of increased sensitivity at high flows within the flow distribution curves.

4.4 Bedload modelling results

The BAGS sediment transport equations were applied to the flow record from each inter-survey period (1987-1993, 1993-1998, 1998-2004 & 2004-2009).

As previously mentioned, different options for the sediment size distribution curves were used. For the armouring layer equations a composite curve was used. A separate curve was used for the whole of bed for the substrate-based equations.

In addition, two different of flow distributions were used in the BAGS equations. The flow distribution with the increased high-end sensitivity was considered to be the more realistic. It is therefore these results that are discussed below.

The results from all of these BAGS equations were converted from a bedload transport rate (kg/s or tonnes/day) to a total bedload volume. This was based on the duration of the inter-survey period, and an estimate of the bulk density of the sediment.

Ministry of Works and Development (1973) cites the bulk density of *"loose, well graded, clean sand-gravelly sand"* as between 1440 and 1600kg/m^3. A conversion rate of 1600kg/m^3 was used for the present study. It is possible that this will produce slightly conservative estimates of sediment volume in the current study.

The total volume, in tonnes, for each of the inter-survey period has been summarised in Table 4.1, and illustrated in Figure 4.5. These bedload transport volumes are compared with those derived from the analysis of changes in the surveyed cross-sections (Opus, 2010a). It should be noted that this is a comparison of only the bedload transport volume calculated here, and not the total sediment load. This explains the significant difference between the two sets of results.

The best representative of bedload movement past Taita Gorge is provided by the Wilcock and Crowe equation, the composite sediment size distribution, and the increased sensitivity of the flow distribution curve. This result was therefore used when calculating the total modelled sediment discussed in Section 6.

Table 4.1: Results of BAGS bedload transport modelling (volume of bedload, m^3).

Period	GWRC total sediment volume	W&C (980&720)	Parker (980&720)	P,K&M (720)	P&K (720)
1987-1993	470,848	34,171	11,653	17,521	16,242
1993-1998	376,850	37,537	13,838	21,853	21,747
1998-2004	591,824	62,721	26,046	48,371	47,289
2004-2009	455,940	44,290	18,774	37,621	35,338

Note: The letters in the above table refer to the particular bedload transport equation used; and the numbers in brackets is how the sediment size distribution was derived – see text for more detail.

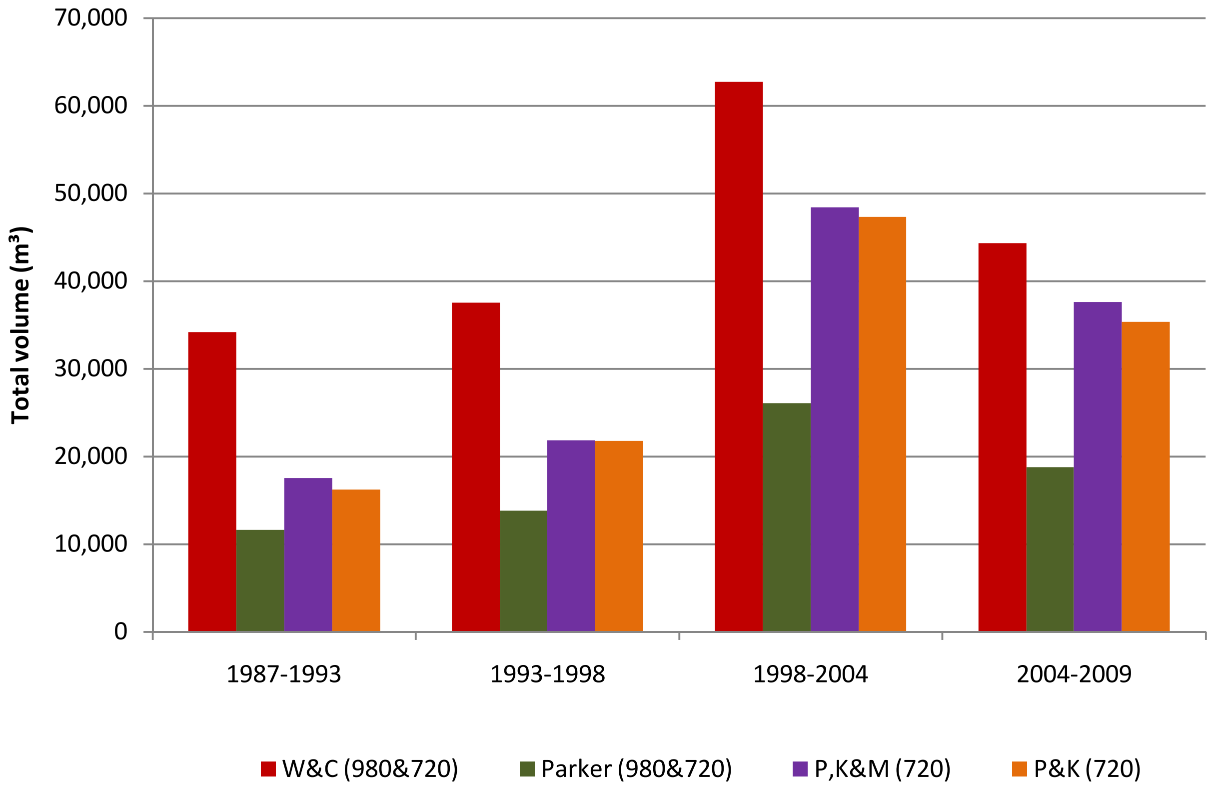

Figure 4.5: Results of BAGS modelling using the recommended sediment size curves and increased high end sensitivity flow distribution curves for each inter-survey period.

5 Suspended sediment

Bedload is, however, only one component of the load transported past Taita Gorge. Consideration of the suspended sediment load is also required to develop a complete sediment budget.

Total suspended load is equal to the integral of concentration and discharge over time, i.e.:

$$\text{Total suspended sediment load} = \int_0^T CQ\,dt$$

Because of the influence of velocity on particle entrainment and transport, combined with the variation in velocity with depth and position in the cross-section, suspended sediment concentration varies with particle size, depth, position across the channel, and time. Therefore quantifying suspended sediment load is very difficult and requires depth-integrated suspended sediment concentration measurements.

It is possible to determine a relationship between sediment concentration and therefore sediment discharge, and flow discharge. From this relationship it is possible to use the flow record to quantify the total suspended sediment discharge. This justifies the effort required to develop the initial empirical relationship between discharge and sediment discharge.

Williams (1991) developed suspended sediment rating curves for the Hutt River at both Taita Gorge and Birchville. No suspended sediment information has been collected for the Hutt River since that time. The sediment rating curve derived for Taita Gorge has therefore been used to estimate the volume of suspended sediment transported over time using the long term flow record at this site.

The suspended sediment volume was calculated for each of the inter-survey periods using a formula derived by Williams (1991):

$$S = \frac{0.014}{1000} Q^{2.82}$$

The above relationship between flow and suspended sediment concentration was applied to the flow record. The resulting suspended sediment load was converted to a suspended sediment volume using a bulk density of 1600kg/m^3. The total suspended sediment volume for each inter-survey period is listed in Table 5.1.

Table 5.1: Calculated inter-survey period suspended sediment volume (m^3).

Period	Total suspended sediment volume (m^3)
1987-1993	409,280
1993-1998	477,512
1998-2004	771,630
2004-2009	419,323

6 Net sediment balance

The modelled total volume of sediment transported by the Hutt River past Taita Gorge can be calculated by adding that transported as bedload material to the suspended sediment. This calculation does not include the dissolved load. From the perspective of channel stability and sediment extraction, the dissolved load is not relevant. That component of the total load is transported out of the system.

The total volume of sediment transported past Taita Gorge over each inter-survey period is shown in Figure 6.1. A summary of the total modelled sediment load is listed in Table 6.1.

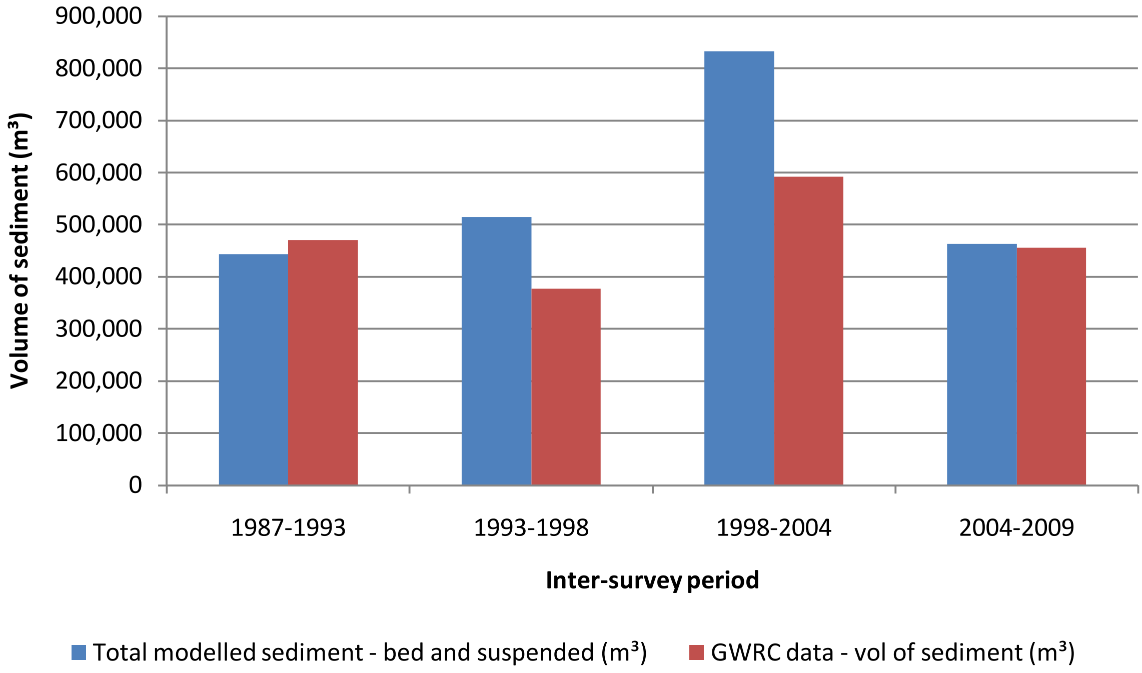

Figure 6.1 Comparison of total sediment volumes estimated from modelling and cross-section analysis.

The percentage of the total volume made up of bedload is also listed is Table 6.1. Hicks & Griffiths (1992) suggest that the bedload transport is typically 3-10% of the total load, or up to 25% for low gradient New Zealand rivers. The results listed in Table 6.1 are consistent with these estimates, and therefore appear realistic. A graphical representation of the proportions of bedload and suspended sediment over each inter-survey period is shown in Figure 6.2.

Table 6.1: Total modelled sediment load for 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 (%)
1987-1993	409,280	34,171	443,451	7.7
1993-1998	476,673	37,537	514,210	7.3
1998-2004	770,224	62,721	832,945	7.5
2004-2009	418,636	44,290	462,926	9.6

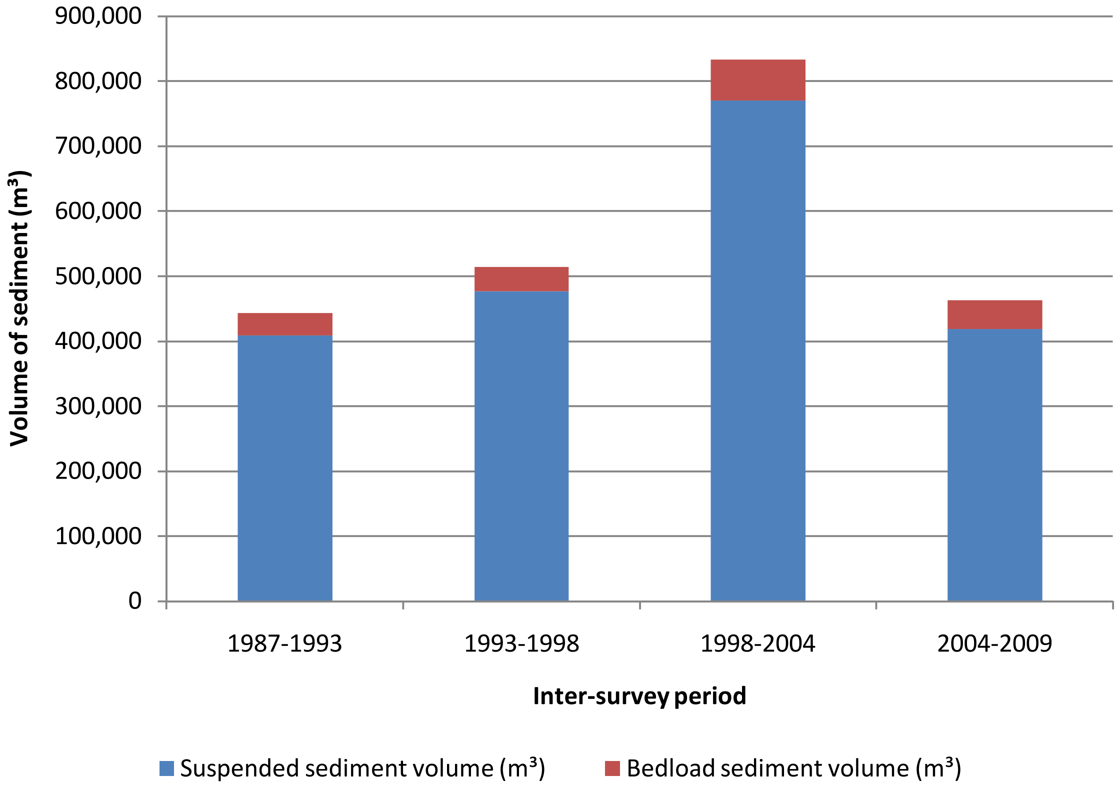

Figure 6.2: Suspended load and bedload as a proportions of total sediment transport.

6.1 Calibration

The modelled total volume of sediment transport was compared to estimates derived using the gravel extraction data and cross-section change information summarised in Opus (2010a).

The comparisons provided in Table 6.2 and Figure 6.1 show that the modelled results are consistent with other sources of information, and are therefore credible. Although there are differences up to 40%, given the nature of sediment modelling, these are considered acceptable. Much of the variation between the total volumes estimated by each method relates to sediment either deposited downstream of cross-section 30, or transported past the river mouth and deposited in Wellington Harbour.

Table 6.2: Total modelled and GWRC volume of sediment.

Period	Total modelled sediment - bed and suspended (m^3)	GWRC data - vol of sediment (m^3)	Percentage difference
1987-1993	443,451	470,848	-5.8
1993-1998	514,210	376,850	36.4
1998-2004	832,945	591,824	40.7
2004-2009	462,926	455,940	1.5

7 Average annual sediment transport

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 from the analysis of cross-section changes and sediment extraction over the same period (Table 7.1).

There is a high degree of variation in the amount of suspended sediment, bedload, and consequently total load, 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. A greater degree of variation is apparent in the modelled results when compared to 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. The results from the analysis of cross-sections are the average net change in material over the reach, and not a measure of actual sediment transport.

Table 7.1: Annual average sediment volumes.

Period	Annual average suspended sediment volume (m^3)	Annual average bedload sediment volume (m^3)	Annual average total sediment load (m^3)	Annual average GWRC total volume (m^3)
1987-1993	69,176	5,776	74,952	79,582
1993-1998	102,354	8,046	110,400	80,777
1998-2004	128,634	10,456	139,090	98,660
2004-2009	83,876	8,859	92,735	91,200
Long term 1987-2009	***96,282***	***8,282***	***104,564***	***87,835***

8 Conclusions

The potential transport of both bedload and suspended load has been calculated for the lower Hutt River. These estimates are based on the sediment size characteristics and flow record from Taita Gorge. This is considered appropriate given that there are no significant inputs of either sediment of water downstream of this location.

The results indicate that:

- The average annual sediment transport past Taita Gorge is 104,564m^3/year. The total load is composed of all material transported as either suspended load or bedload.

- The sediment transport rate calculated compares favourably to that calculated in Opus (2010a) of 87,835m^3/year. The difference relates largely to material deposited downstream of cross-section 30 and beyond the river mouth. This material is not considered in Opus (2010a), although it is discussed in Opus (2010b).

- Of the total sediment transport approximately 8% is bedload. The remaining 82% is suspended sediment. These estimates are consistent with other New Zealand data.

- There is a high degree of variability in sediment transport. This relates to flow variability within the Hutt River.
- The annual rate of sediment transport since 1987 has ranged from 75,000 to 139,000m^3.
- Annual sediment transport is controlled largely by the number, magnitude, and duration of flood events.
- 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, there is a high degree of inter-annual variability.
- Lower than average rates of sediment accumulation since 2004 likely reflects the lack of significant flood events over this period.
- It is likely that an average annual sediment transport rate of approximately 88,000m^3 is indicative of the long term sediment transport regime.

9 References

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