DOWNSTREAM FINING IN THE WAIPAOA RIVER; AN AGGRADING, GRAVEL - BED RIVER, EAST COAST, NEW ZEALAND.

Brenda J Rosser

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Abstract

The Waipaoa River, East Cape, New Zealand, drains a catchment from the Raukumara Ranges into Poverty Bay, near Gisborne. Conversion of the catchment from indigenous forest to pasture, between 1880-1920, initiated a phase of intense erosion in the hill country. The underlying geology consists of crushed and sheared sandstone, siltstone, argillite, and mudstone of Cretaceous and Tertiary age. Channel aggradation occurred in response to the influx of bed material load. Suspended sediment yields in headwater catchments are as high as 7 000 - 17 000 t km^{-2} yr^{-1}. For the period 1948 to 1988, aggradation in the upper reaches was > 5 m, while in the lower reaches it was ~0.5 m. The Waipaoa River is a gravel-bed river. Its morphology changes from a braided to a meandering configuration in the downstream direction.

A bed material survey of the Waipaoa River in 1995/6 investigated the fluvial transfer of coarse bed material through the river system. Bed material samples were collected at 1 km intervals along the mainstem, as well as from major tributaries, near their confluence with the Waipaoa River. Surface and subsurface samples were systematically collected between the coast and 104 km upstream. The results of this survey were compared with earlier bed material surveys undertaken in 1950, 1956, and 1960.

Results of the 1996 bed material survey indicate that the bed material in the Waipaoa River is polymodal. The gravel-sand transition occurs approximately 8 km upriver from the coast. Over the remaining 96 km reach, the median particle size (D_{50}) declined from 5 mm in the headwaters, to 2 mm near the coast. The coarser particle size fractions exhibited a greater rate of downstream fining, and, over the same distance, the coarsest 10% (D_{90}) declined from 48 mm to 6 mm. The bed material is dominated by fine sediment, which is illustrated by the fine median particle size over the length of the river, as well as the low fining coefficients for the finer particle size fractions ($< D_{50}$). No downstream change in the proportion of each main pebble lithology was observed, and each pebble lithology exhibited a similar rate of downstream fining. No downstream alteration in particle shape was observed, although particle roundness did increase downstream. Close relationships were observed between the bed slope and particle size. The highest degree of correlation was observed between slope and the coarsest particle size fractions, representing the limiting condition of channel competence. Selective transport is the dominant process that produces downstream fining in the Waipaoa River, however, particle fragmentation, sediment supply or abrasion may be important processes within specific reaches. The rate of downstream fining was consistent for the period 1948 to 1996.

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TABLE OF CONTENTS

LIST OF FIGURES

List Of Tables

1. INTRODUCTION 1.

It is widely recognised that the hydraulic characteristics of natural rivers change in the longitudinal direction (Richards, 1982; Knighton, 1980, 1982). Perhaps the most important of these characteristics, the bed material, is observed, in most gravel bed rivers, to decrease in size downstream. Bed material composition and structure are closely tied to contemporary conditions (Diplas and Fripp, 1992), although, the size distribution of the bed material also can be considered to be representative of the average bed load carried over an extended period of time (Lisle, 1995). The reduction in size of bed material in the downstream direction usually is attributed to a combination of selective transport of the more mobile smaller grains by the current, and particle attrition through breakage or abrasion during transport (Shaw & Kellerhals, 1982). Diminution coefficients in natural rivers range from ~0.001 mm km^{-1} for chert pebbles in the Colorado River, USA (Bradley, 1970), to 9.3 mm km^{-1} in the Allt Dubhaig, Scotland (Ferguson & Ashworth, 1991). The rate of downstream fining depends on the specific hydrological conditions in the river catchment, as well as on the size and lithological composition of the material supplied to the river.

An extensive bed material investigation was conducted on the Waipaoa River, East Cape, New Zealand, in order to characterise the channel sediment, and to elucidate the processes that contribute to the fluvial transfer of sediment through the Waipaoa River system. The Waipaoa River catchment has a recent history of erosion, which, since the late 19^{th} century, has produced high sediment supply rates to the channel system. As a consequence, the Waipaoa River is aggrading. Historical accounts, cross section surveys, and bed material surveys conducted over the past fifty years have contributed to understanding the response of the river to an increased sediment supply.

The primary objective of this study was to determine the relative importance of selective transport, abrasion, and other process that may operate in the Waipaoa River to produce downstream fining. This objective may be achieved by the completion of several elementary objectives. These elementary objectives were to characterise the size, shape, and lithology of the sediment currently moving through the Waipaoa River system, and in doing so identify and explain trends of changing particle size in the downstream direction. The relationships between the observed downstream changes in particle size with various hydraulic and morphologic variables also were sought. An attempt was made to establish the effect of the catchment geology on the river system, as well as to determine the relative importance of tributary and riparian sediment inputs to the river channel.

The downstream fining of river bed sediments has long been a topic of debate among geomorphologists and fluvial sedimentologists. Since the first studies that were undertaken by M.Darcel, H.Sternberg and A.Daubree, in the late nineteenth century (Mikos, 1993), numerous researchers have sought to elucidate the factors contributing to the size reduction of bed material in the downstream direction. Initially, the downstream reduction in particle size was attributed solely to the abrasion of sediment during its passage through a river system. Fluvial abrasion is the reduction in size of sediment particles effected by mechanical processes, such as grinding, chipping, and splitting, or weathering (Mikos, 1993). In 1875, H.Sternberg proposed that the downstream decrease in particle weight was exponentially proportional to the size of the original particle and the distance travelled. Assuming a constant weight reduction factor, Sternberg's equation can be written as

$$W = W_0 e^{-\alpha L} \qquad (1.1)$$

where W is the weight of a characteristic particle at distance downstream L; W_o is the initial weight of the characteristic particle at L=0; and α is the weight reduction coefficient.

Early studies of downstream fining focused primarily on pebble abrasion through the study of roundness, and on the definition of the factors controlling the speed and character of abrasion. A number of investigations were carried out under laboratory conditions in tumbling mills. Among the first pebble abrasion experiments were those performed by A.Daubree in 1879 (Mikos, 1993). From these tumbling mill experiments a number of fundamental principles pertaining to the abrasion of pebble sized sediments were derived. For example, it was observed that angular particles wear faster than rounded particles, and larger particles wear faster than small particles. The products of abrasion predominantly were also found to be in the silt-clay size range. A.Daubree probably was the first to recognise that downstream fining could not be explained by abrasion processes alone due to the discrepancy between abrasion rates measured in the laboratory and those observed in the field (Mikos, 1993). This notion was reinforced by subsequent studies of abrasion undertaken both in natural rivers and in laboratory experiments (*eg*. Krumbein, 1941; Kuenen, 1955; Shaw & Kellerhals, 1982).

In the period 1919-1931, C.K.Wentworth made several notable contributions to the study of pebble abrasion. Wentworth (1919) observed that the fundamental characteristics of particles that may be modified by abrasion; namely their size, shape and surface texture, are controlled by a range of factors that include particle size, angularity, and lithology, the type and nature of motion, the distance travelled, and the size and number of associated particles that also are in motion. Wentworth also suggested that a negative exponential function might be used to describe the decrease in particle size that occurs with increasing distance downstream (Krumbein, 1941).

Field observations and laboratory experiments undertaken by A. Schoklitsch in the early 1930's validated Sternberg's equation (Mikos, 1993). Schoklitsch also proposed that equation 1.1 might be expressed in terms of particle volume or diameter. By studying the abrasion of a single particle of predetermined dimensions and weight, within a sediment mixture, Schoklitsch observed that the abrasion of particles linearly is related to the particle size distribution of the mixture within which it is entrained. The fining coefficient (α) was related to, and should be constant for, a specific pebble lithology.

The relationships between pebble size, shape, and roundness during abrasion in tumbling mills were explored by Krumbein (1941). He observed that the resulting pebble shape generally reflected the shape of the original particle, and changed little over time. Krumbein (1941) recognised that, in many instances, abrasion yields characteristically shaped pebbles, and that particle size decline resulting from abrasion proceeds very slowly.

Plumley (1948) studied particle size reduction rates in rivers in the Black Hills, South Dakota. He found that the reduction in particle size experienced in these rivers could not be predicted by Sternberg's equation. Instead, Plumley (1948) considered that downstream fining was a function of bed slope and the longitudinal profile of the river. He argued that if abrasion alone was occurring in natural rivers, rapid abrasion of coarse particles (compared to fine) would act to normalise the particle size distribution. In this case the particle size distribution would be expected to exhibit a positive skewness in headwater reaches and a negative skewness downstream. Since no evidence for this change in skewness was found, Plumley (1948) concluded that the selective transport of smaller particles was the more likely cause of downstream fining. Plumley (1948) also studied particle shape changes in the downstream direction. He concluded that particle shape was a function of particle size, but found there were no systematic downstream changes in particle shape, due to particle breakage.

Abrasion experiments prior to the 1950's were carried out in tumbling mills that poorly represent the conditions in which sediment transport occurs in natural rivers. The main concern was that the water in a tumbling mill inhibited particle motion, whereas water encourages particle motion in natural rivers (Kuenen, 1955). Kuenen (1955) developed a circular flume to study abrasion under conditions that better reflect particle motion in natural rivers. He studied pebble rounding and found that if sand was entrained with the pebbles, the cushioning effect of the sand reduced the rate of rounding.

Riparian and tributary inputs interrupt the general trend of downstream fining (Miller, 1958). Miller (1958) also determined that the abundance of a particular lithology in the bed material was related to the ease of weathering, size of the source area and resistance to abrasion in the channel. Jointing and weathering characteristics explain differences in the maximum size of a given lithology. In addition the bed material composition of a river below the confluence of two tributaries was an average of the lithologies supplied by the two rivers, and the bed material usually became throughly mixed within a short distance downstream. No consistent downstream changes in sorting or particle shape were observed in the New Mexican rivers Miller (1958) studied.

Weathering before or during transport is an important factor controlling the susceptibility of particles to abrasion (Bradley, 1970). Tumbling mill abrasion experiments traditionally use uniform, fresh material of predetermined roundness and shape (Kuenen, 1955), but the rate of abrasion increases tenfold if weathered material is used (Bradley, 1970). This better reflects the abrasion rate in natural rivers. It has been suggested (Kuenen, 1955), that, with the exception of poorly consolidated or fissile rocks, pebbles rarely are split by collisions, although fractured particles are quite common in pebble deposits. Kuenen (1955) attributed the common occurrence of fractured particles to weathering (particularly by frost action) of pebbles during storage in flood plain deposits. The entrainment and subsequent breakdown of weathered granitic material in the headwater streams of the Southern Alps, New Zealand, was shown to be the main factor contributing to downstream fining in these streams (Adams, 1979).

In situ size reduction also may occur due to the vibration of particles at flow velocities below those critical for particle entrainment (Schumm & Stevens, 1973). In gravel bed rivers, the time a gravel particle spends at rest is far greater than the time spent in motion (Einstein, 1933). This perhaps suggests that size reduction is not solely a function of transport distance (Shaw & Kellerhals, 1982). Near bed turbulence, even at low and moderate flows, is sufficient to cause particles to vibrate (Clifford *et al.*, 1993). Shaw and Kellerhals (1982) determined that, of the total abrasion occurring in Albertan rivers, over 90 % was attributable to *in situ* abrasion processes .

The rate of size reduction observed in the field generally is much larger than the rate that can be attributed to abrasion alone, other processes therefore must contribute to particle size reduction (Kuenen, 1955). The obvious process is that associated with the transport of fluvial sediment as bed load. Einstein (1950) demonstrated that transport rates for individual size fractions vary inversely with grainsize, so that the finer size fractions may have a transport rate that is several orders of magnitude greater than the rate for the coarse fractions. This lead to the concept of selective transport as a mechanism for producing downstream fining.

Size selective entrainment is associated with the notion that each size fraction is entrained by the current only when the critical shear stress for that specific size is attained (Ashworth and Ferguson, 1989). A related process, selective distrainment, is the process by which grains are preferentially deposited on the channel bed (Whiting, 1996). Distrainment may be occasioned by a decrease in the magnitude of the fluid forces keeping grains in motion, or because the geometry of the bed surface encourages the deposition of certain grain sizes. Selective transport represents the combined effect of selective entrainment and distrainment, since particle transport typically involves repeated entrainment and deposition events (Whiting, 1996). Selective transport therefore implies that finer grains are preferentially transported downstream farther and faster than larger grains (Plumley, 1948; Kodama, 1994), and that the particle size of individual grains is conserved (Parker, 1991). Selective transport is confounded by the notion that coarse particles on a fine bed experience enhanced mobility (Whiting, 1996). The particle size distribution of the sediment mixture therefore must be taken into account.

Particle size differences at the bar scale also may contribute to downstream fining (Bluck, 1987). Coarse particles are transported downstream until a sufficient concentration is established in the bed. Large bed forms, such as bars, act as coarse sediment traps encouraging the deposition of coarse material at the upstream ends of bars, progressively starving downstream units of coarse sediment (Clifford *et al.*, 1993).

Selective transport and downstream fining are related to the downstream decrease of hydraulic variables such as flow competence. The longitudinal profile of most rivers is concave, indicating that bed slope decreases downstream (Yatsu, 1955; Ferguson & Ashworth, 1991). Uniform sediment transport conditions require a constant bed slope (Parker, 1991b), so a decrease in slope without a corresponding increase in discharge causes the boundary shear stress to decrease. Thus a decrease in bed load transport capacity for a given size fraction downstream is implied (Ashworth and Ferguson, 1989). Slope usually is reported to be related to particle size. Miller (1958) concluded that slope, is in part related to the areal distribution of the underlying geology, and that bed slope is a partially independent variable, which a stream can modify within certain limits.

Changes in channel slope have long been explained in terms of particle size (Wilcock, 1967). H.Sternberg (1875) considered the longitudinal profile of a river was concave. The downstream decrease in slope was adjusted to the bed material size, which decreased due to fluvial abrasion. G.K.Gilbert (1914), by contrast, emphasised that discharge increased downstream. He proposed that bed slope decreased downstream because a lower gradient was required to transport the supplied material. The concepts of Sternberg and Gilbert were integrated by Rubey (1952), who proposed that bed slope and channel form were dependent variables that mutually adjust to the imposed conditions of sediment calibre and quantity, and water discharge, such that

$$S^3 = k \frac{L^2 M}{Q^2 X} \tag{1.2}$$

where: S is slope, L is the sediment load quantity, M is the sediment load size (D_{50}), Q is discharge, X is an index of cross section shape, and k is a constant. Rubey's equation indicates that there is a positive relationship between slope and bed material size, and a negative relationship between slope and both discharge and cross section shape (Penning-Rowsell & Townshend, 1967). For a given constant discharge and cross section shape, slope therefore is directly proportional to particle size. This arises because of the balance that exists between the tractive force and particle size (Yatsu, 1955). Strong empirical support for the concept of channel adjustment involving channel form, gradient and cross-section shape was provided by Miller (1991). Adjustments to bed slope are assumed to be effected by aggradation and degradation. The slope is presumed to be sufficient to transport the size and volume of sediment supplied to the channel from upstream (Mackin, 1948).

Wilcock (1967) concluded that bed slope is determined by the coarsest size fractions of the bed material that are seldom entrained, except in rare, extreme flood events. Hack (1957) found no simple relationship between bed material size and river channel slope in streams in Virginia and Maryland, except within lithologically homogeneous areas. However, a good correlation was obtained with drainage area, which was employed as a surrogate for discharge. Catchment area and average annual discharge both increase directly in proportion to the other and often are interchanged (Penning-Rowsell & Townshend, 1978). Hack (1957) concluded that bed slope and sediment size were inter-dependent, and that a dynamic equilibrium exists between slope, sediment size and discharge. Pizzuto (1992) established that Hack's (1957) conclusions were a manifestation of the same equilibrium processes which produce the hydraulic geometry relations. Pizzuto (1992) regarded grainsize as an independent variable, and slope as a dependent variable. It was suggested by Pizzuto (1992) that, locally, slope was likely to be out of equilibrium with the bed material size, because of the comparatively long time scale required for slope adjustments. Channel width and depth, respectively, were considered most likely to be in equilibrium with current conditions (Pizzuto, 1992).

Penning-Rowsell and Townshend (1978) addressed the concept of scale and recognised the need to relate the spatial patterns and forms to the correct process, at the right spatial and temporal scale. Depending upon the scale at which the river system is examined, morphologic variables can either appear to be independent or dependent, so that apparent cause and effect will depend upon the scale employed (Schumm & Lichty, 1965). Penning-Rowsell and Townshend (1978) concluded that local bed slope was closely related to surface bed material size, and that reach slope was closely related to a discharge index (contributing basin area).

The longitudinal profile of a river traditionally has been described by an exponential curve (Yatsu, 1955). Ikeda (1970) concluded that rivers that exhibit a rapid rate of particle attrition will have a longitudinal profile that exhibits a greater concavity, in comparison to rivers that exhibit a low rate of particle attrition. Ohmori (1991) observed that the mathematical function best describing the longitudinal profile of Japanese rivers was dependent upon the fluvial processes operating within the river, and its evolutionary stage. Rivers whose longitudinal profiles were described by exponential functions were most likely to be in a depositional stage, and to be aggradational. Rivers that were described by power functions were most likely to be in a transportational phase, and to be subject to degradation. Those rivers described by linear functions were likely to be in a state of balance, and the sediment supply equals the sediment discharge (Ohmori, 1991). In the Japanese rivers studied by Ohmori (1991), sediment supply rates were high, and aggradation was common in the middle reaches. The form of the longitudinal profile tended to evolve from an exponential function, through a power function, to a linear function by means of aggradation.

Church and Kellerhals (1978) demonstrated that downstream fining must be considered as the combined effect of selective transport and abrasion, operating together, albeit at different rates. The effects of both selective transport and abrasion decrease exponentially in the downstream direction. Subsequent investigations have been directed towards defining the relative importance of selective transport, abrasion, and other processes that may be responsible for producing downstream fining in specific settings. There has been much debate concerning this topic in recent literature (Paola & Seal, 1992; Mikos, 1993, 1994; Huddart,1994; Rice, 1995; etc).

The relative importance of selective transport and abrasion was considered by Shaw & Kellerhals (1982) to be determined by a river's geomorphological state. In aggrading reaches, where bed material progressively is buried, and therefore unavailable for reworking and abrasion, selective transport will be the dominant process. In degrading reaches, where bed material is constantly reworked, abrasion is likely to be the dominant process. It is therefore implied that differential transport produces more rapid downstream fining than abrasion, on account of the slow rate of particle size reduction that is associated with abrasion (Krumbein, 1941). For this reason, Shaw & Kellerhals (1982) stressed the importance of identifying antecedent processes that may exert an underlying control on the observed pattern of downstream fining in a river system.

Under equilibrium sediment transport conditions, in which sediment discharge is approximately equivalent to sediment supply (Germanoski & Schumm, 1993), material in the bed load and the surface layer are constantly interchanging (Toro-Escobar *et al.*, 1996). The occurrence of aggradation or degradation in natural river channels implies the existence of non-equilibrium conditions between the flow of water through the channel, and the sediment transport rate (Hoey & Sutherland, 1991). In the case of degradation, the substrate is incorporated into the surface layer as the bed degrades. In the case of aggradation, the surface material is transferred to the substrate as the bed aggrades (Toro-Escobar *et al.*, 1996). Aggradation occurs either because of an increase in sediment supply, which causes overloading, or because of a decrease in water discharge (Ribberink & Van Der Sande, 1985). In both cases the sediment supply is greater than the sediment transporting capacity of the river.

Downstream fining observed in aggrading channels often is reported to proceed at a faster rate than in degrading channels (eg., Shaw & Kellerhals, 1982). The transfer of material from the surface to the subsurface during aggradation inhibits extensive reworking of the deposit. This process moderates the effect of abrasion, because particles are not available for reworking. Under conditions of aggradation, downstream fining is more rapid because the effect of selective transport is enhanced. This may arise because the gradient is adjusted to transport the quantity rather than the size of sediment supplied to the channel. Howard (1980, 1987) suggested that the channel gradient might be adjusted so as to transport the more numerous particles near the median grain size, thus enhancing size selective entrainment. This hypothesis differs slightly from the common observation that bed slope is adjusted to the coarsest size fractions of the bed material, in equilibrium channels (Wilcock, 1967).

If abrasion is an important process occurring in a river system, downstream fining occurs because the supply of material to downstream reaches is progressively finer (Whiting, 1996). Parker (1991b) stated that selective transport was likely to be the most important mechanism producing downstream fining in most natural rivers, with the exception of rivers that carry a high proportion less resistant lithologies, which abrade rapidly in response to related processes such as mineral solution.

Fluvial abrasion recently has received renewed attention with the work of Kodama (1994 a,b) and Mikos (1993, 1994). Abrasion was found to be the dominant process contributing to downstream fining in the Waterase River, Japan (Kodama, 1994). The lithology of the bed material changed dramatically within a 20 km reach of the Waterase River, with chert increasing in abundance downstream at the expense of all other lithologies.

Mikos (1993) undertook laboratory experiments and a field study of the sediments in the Alpine Rhine River, Switzerland, and developed two abrasion models to replace Sternberg's model. Mikos (1993) found no unique expression of fluvial abrasion because the intermittent nature of sediment transport produced a different abrasion history for each pebble. The main differences between the model derived by Sternberg and those proposed by Mikos (1993) are the incorporation of a weight reduction coefficient that decreases with distance downstream, and a linear wear rate that is defined for each size fraction, rather than for individual particles. The use of a fining coefficient that varies with distance also was favoured by Brierly and Hickin (1985).

Downstream fining was induced in a laboratory flume by Paola *et al.* (1992) solely by the process of selective deposition (distrainment). Abrasion was precluded because of the short amount of time and short transport distance involved. Paola *et al.* (1992) found that neither a variation in discharge nor in the pre-existing slope was required to produce downstream fining. The decrease in particle size was related to the constant upward concavity of the longitudinal profile, indicating a downstream decrease in the required slope for particle motion. This was taken to imply that the observed downstream fining was an integral part of the simulated river, to which the slope adjusted. Downstream fining was the result of a decreasing amount of total sediment movement (due to deposition), and the decrease in grain size (due to selective deposition). The resultant bed slope was sufficient to transport the material provided from upstream. The fining pattern was set up early in the experiment, and was maintained as the bed aggraded and the gravel front propagated downstream. Paola *et al.* (1992) concluded that the only requirement necessary to induce downstream fining was the transport and deposition of a sufficiently poorly sorted or bimodal sediment mixture.

Pickup (1984) suggested that downstream fining was a reflection of the changing proportions of gravel and sand in a bimodal sediment mixture, rather than of a gradual decrease in mean particle size. This assumes that particles comprising the coarse mode of the bimodal sediment will break up into their constituent particles, to form the fine mode. If it can be proven that this occurs, then there is no need to invoke the occurrence of either selective transport or abrasion as mechanisms for producing downstream fining (Wolcott, 1988). Thus the particle size distribution of the input material from the source area, tributaries and bank erosion ideally should be characterised prior to any investigation (Wolcott, 1988). Sandstone has been shown to break up into its constituent grains rather easily, forming a bimodal sediment mixture comprised of sand and gravel (Wolcott, 1988). This process provides a non-fluvial control on downstream fining, and affords an explanation for the occurrence of bimodal sediments.

Fluvial sediments often are reported to be bimodal, with peaks in the gravel and sand size ranges (eg. Shaw & Kellerhals, 1982). Bimodality of fluvial sediments traditionally has been attributed either to the influence of the parent material (rock type) (Walcott, 1988; Shaw & Kellerhals, 1982), the preferential breakdown of fine gravel into sand and silt particles (Yatsu, 1955; Moss, 1972a; Kodama, 1994), or the preferential entrainment of fine gravel, leaving a residual deposit composed of coarse gravel and sand (Sundborg, 1956; Russell, 1968). If sediments are not bimodal at the source, they may become so in the downstream direction, due to the addition of fine material from either the abrasion of gravel, or inputs of sediment to the main channel from tributaries or bank erosion.

Shaw & Kellerhals (1982) suggest that bimodality in Albertan rivers is caused by the rapid breakdown of 1-4 mm particles by crushing and abrasion during transport. The coarsest fractions essentially are the most stable, and the lack of particles in the 1-4 mm size range was explained in terms of transport mode. Medium sand is the coarsest material carried in suspension, whereas coarse sand and fine gravel constitute the finest fractions of the bed load. This means that coarse sand and fine gravel suffer maximum attrition by crushing and abrasion during transport and are therefore eliminated. Medium sand is deposited from suspension into the interstices between coarse grains as the flow recedes forming a bimodal sediment mixture (Shaw & Kellerhals, 1982).

Sambrook-Smith (1996) suggests that bimodal fluvial sediments may represent a distinct threshold between gravel- and sand-bed channels. Bimodal bed material commonly is found in river channels that undergo a rapid transition from a gravel- to a sand-bed. Sambrook-Smith and Ferguson (1996) simulated a gavel-sand transition by employing a bimodal sediment mixture of gravel and sand in a laboratory flume. With each successive run, the flume was subjected to progressively lower slope. Successive runs therefore represented sites along a concave longitudinal profile of a river approaching a local fixed base level (Sambrook-Smith & Ferguson, 1996). Variations in bed surface texture and pattern, and flow properties were recorded over the transition, affording information on the processes that occur at gravel-sand transitions. With decreasing slope, the bed material became progressively more bimodal as the sand fraction became dominant and the gravel fraction became less mobile (Sambrook-Smith & Ferguson, 1996). The bed load underwent a series of changes from a fully mobile gravel bed, where sand was carried in suspension and gravel was carried as bedload, to a bed surface with increasing amounts of sand, where sand was carried as a continuous sand sheet, and the gravel was virtually immobile (Sambrook-Smith & Ferguson, 1996). In response to the increasing dominance of sand in the bedload, the bed surface showed a progression from a gravel bed with limited sand on the surface, through various transitory bed types, to a sand bed surface with ripples and dunes (Sambrook-Smith & Ferguson, 1996).

Flow properties were affected by the finer surface and decreased friction, and adjusted to the imposed conditions (Sambrook Smith & Ferguson, 1996). Sambrook-Smith and Ferguson (1996) observed that the bed progressively segregated into areas of gravel and sand as the slope declined. The segregation of sand and gravel into 'patches' on the bed surface has been suggested as a mechanism that may enhance downstream fining. Equal mobility of all size fractions is achieved within a patch, but size selective entrainment occurs across the channel width to produce downstream fining (Paola & Seal, 1995). The arrangement of the bed surface into areas of coarse and fine sediment seems to offer further explanation of the relatively short distances involved in many gravel sand transitions.

The sudden transition from gravel to sand was explained by Howard (1980, 1987) in terms of a geomorphological threshold, due to the gradient required to transport certain grain size fractions. Using sediment transport formulae, and assuming that a channel tends towards an equilibrium gradient sufficient to transport the imposed sediment load with the available discharge, Howard (1980, 1987) developed a model to predict the required gradient, where the relationship between gradient and grain size depends on the supply of coarse material. At some maximum grain size, the supply of coarse material will not be sufficient to form a bed layer. If the gradient required to transport the coarse fractions of the bed material is greater than that required to transport the volume of finer particles supplied, fine material will not be deposited and the bed will be coarse grained. If however, the gradient required to transport the coarser size fractions is less than that required to transport the quantity of fine material supplied, a sand bed will form. It seems that a compromise is made between the competence of a channel to transport the coarser size fractions, and the capacity to transport the volume of fine material supplied (Sambrook Smith & Ferguson, 1996).

In a downstream direction, characteristic parameters describing individual particles as well as the sediment mixture are expected to change. Abrasion can be inferred to be the dominant mechanism of downstream fining in situations where less durable lithologies decrease in size, or change shape more rapidly than mechanically durable rock types. However, if all rock types show similar rates of change of clast and mixture parameters with respect to distance, selective transport is inferred the dominant process. Selective transport should theoretically produce a similar maximum clast size for all rock types, in all parts of the river, assuming that the different rock types have similar densities and shapes (Huddart, 1994). A general increase in sorting of the particle size distribution is indicative of such trends. Selective transport by shape and density has, however, been documented for many natural rivers and streams (Knighton, 1982; Whiting, 1996). Knighton (1982), for example, attributed downstream fining in the River Noe, England, to selective sorting by shape. Disc shaped particles were observed to be larger than any other particle shape, suggesting that disc shaped pebbles experienced enhanced mobility, and were transported farther downstream than other shapes of the same size. Selective sorting by density leads to the formation of placer deposits, where heavier, denser lithologies experience reduced mobility relative to other lithologies of a similar size (Whiting, 1996).

Physically based models have been developed to describe particle size variation at large scales. A quantitative model has been developed by Parker (1991 a,b) that simultaneously incorporates selective sorting and abrasion. The model predicts the variation in channel slope and particle size downstream. Paola *et al.* (1992) and Heller *et al.* (1992) together have developed a two dimensional model of selective deposition that accounts for allocyclic influences on grainsize variations at the basin scale. Allocyclic mechanisms include externally forced processes such as tectonism (uplift and subsidence), climate and gravel flux. The models developed by Paola *et al* (1992) and Heller *et al* (1992) emerged from the equations governing flow and sediment transport in rivers, and predict the downstream limit of gravel progradation, based on the supply of sediment to the river system, and the rate at which sediment is moved through the system. Their model also may be used to interpret vertical grainsize changes (eg. upward coarsening), in sedimentary sequences in alluvial basins. The models described above are capable of generating a downstream fining pattern and rate comparable to that observed in natural streams.

One of the primary sources of the variability that is commonly observed in particle size statistics presented over the length of a river arises from the method used to acquire the particle size data (Church & Kellerhals, 1978). Quantification of the mechanisms producing downstream fining require reliable particle size data that accurately reflect the sediment present in the river channel. Reliable particle size data also are required to test the models of downstream fining, and determine the degree to which the models accurately reflect natural river systems. There are a number of procedures and methods for the collection of representative particle size data. These will be discussed in Chapter 3.

The upper reaches of many gravel bed rivers in New Zealand fine appreciably in the downstream direction (Adams, 1979). The Waipaoa River in New Zealand's East Cape region, is an aggrading river system. Situated on the Eastern side of the Raukumara Ranges, the Waipaoa River drains a 2150 km^2 catchment in which the underlying geology predominantly consists of friable Cretaceous and Neogene sandstone, siltstone, argillite and mudstone. Native forest clearance began in the Upper Waipaoa Catchment around 1875, and the majority of land, including the steep hillslopes in the headwaters, had been converted to pasture by 1910 (Jones & Howie, 1970). This change in land use initiated a phase of widespread and severe erosion. Sediment generated by gullies and mass movements was fed into the channels of the Waipaoa River system, which aggraded and changed from a meandering to a braided configuration in the upper reaches. Channel cross section surveys undertaken at 1 mile intervals along the ~100 km main channel throughout the period 1947 to present, show that >32 million cubic metres of material was deposited in the Waipaoa River in the period 1948-1979 (Hosking, 1985). An estimated 30 m of vertical aggradation occurred in tributaries in the headwater regions since the beginning of forest removal (Jones and Howie, 1970). The amount of aggradation along the main channel ranged between >-5 mm yr^{-1} in the lower reaches, to ~25 mm yr^{-1} in the upper reaches in the period 1948 to 1960, although the rate has declined appreciably in the upper reaches during the last decade. In the Waipaoa River, aggradation was occasioned by an increase in the sediment supply. Aggradation occurs throughout the length of the channel, but it is greatest in the upper reaches, near the sediment source (Hosking, 1985).

The results of the bed material investigation along the mainstem of the Waipaoa River are presented in this thesis. Particle size changes are explored in terms of the relative effects of abrasion, selective transport, and other mechanisms that operate in the catchment. Changes in bed material size are interpreted in terms of local bed slope, reach slope and the longitudinal profile, aspects of the channel cross-section, channel morphology and discharge. The importance of catchment geology, as well as tributary and riparian sediment sources are evaluated. Shaw and Kellerhals (1982) proposed that selective transport is the dominant process contributing to downstream fining in aggrading rivers. Owing to the friable nature of the bedrock material in the Waipaoa catchment, size reduction due to particle breakdown or fluvial abrasion also may play an important role.

The shape and lithologic composition of the >16 mm gravel fraction are determined. Downstream changes in particle size, shape and roundness are related intimately to rock type (Miller, 1958; Mills, 1979; Huddart, 1994). By investigating the behaviour of individual rock types with respect to transport distance, the complexity of the overall pattern of downstream fining, encountered in catchments with varied geology, can be explained (Huddart, 1994). The relative importance of individual processes can be estimated for each rock type, and in doing so enables the relative importance of selective transport, abrasion and other processes (eg. weathering, fragmentation, dilution etc.) producing downstream fining to be evaluated (Huddart, 1994).

Typically studies of downstream fining are carried out under optimum conditions of river equilibrium, with an array of rock types of varying hardness, supplied to the channel from a single sediment source. This study of downstream fining in a rapidly aggrading river system is distinctive in that the geology of the catchment is dominated by soft rocks in a tectonically active environment. Multiple sediment sources from tributaries and bank erosion complicate the downstream trends that otherwise would be expected from a single sediment source.

2. STUDY AREA

The Waipaoa River begins at the confluence of the two headwater streams, Wairangiora and Waimatau, on the eastern side of the Raukumara Ranges, East Cape, New Zealand (Figure 2.1). From here, the river flows in a southerly direction to the coast, flowing into Poverty Bay aproximately 10 km southwest of Gisborne. The mainstem length is 104 km, and the total catchment area is 2181 km^2. Elevation in the catchment ranges from 1440 m, in the highest peaks of the Raukumara Ranges, to sea level at the river mouth.

A number of principal tributaries enter the Waipaoa River in the upper reaches (Fig 2.1): the Waimatau Stream; Wairangiora Stream; Tikihore Stream; Matakonekone Stream; Te Weraroa Stream; and Mangaorongo Stream. Steep alluvial fans occur at the confluence of all the tributaries in the upper reaches, with the exception of Mangaorongo Stream, which carries a high suspended sediment load. The Mangatu River, which contributes two thirds of the Waipaoa River's discharge downriver from the confluence (Smith, 1977), joins the Waipaoa River 2 km upstream from Whatatutu. In the middle reaches, the principal tributaries are the Waingaromia River, Waikohu River and Waihora River. The Te Arai River enters the main channel 5 km from the coast.

For the majority of its length, the Waipaoa River exhibits a gravel bed. On the basis of its morphology, the river can be divided into three reaches (Figure 2.1). The river exhibits a multi-thread braided morphology in its upper reaches, downriver from the confluence of the Wairangiora and Waimatau streams, from 104 km to 92 km (Figure 2.2). In the upstream portion of the middle reaches the river flows through a narrow gorge from 92 km to 77 km, and thereafter (77 km to 45 km) it is entrenched between Pleistocene terraces and low hills. Throughout the middle reaches the river exhibits a single-thread, meandering morphology at high flows, although it has a tendency to braid at low flows (Figure 2.3). In the lower reaches (45 km to the sea) the river meanders across the Poverty Bay flats (Fig 2.4). Engineered cutoffs and stopbank construction, undertaken over the past fifty years as part of a flood control scheme, have had a major influence on the behaviour of the river in the lower reaches.

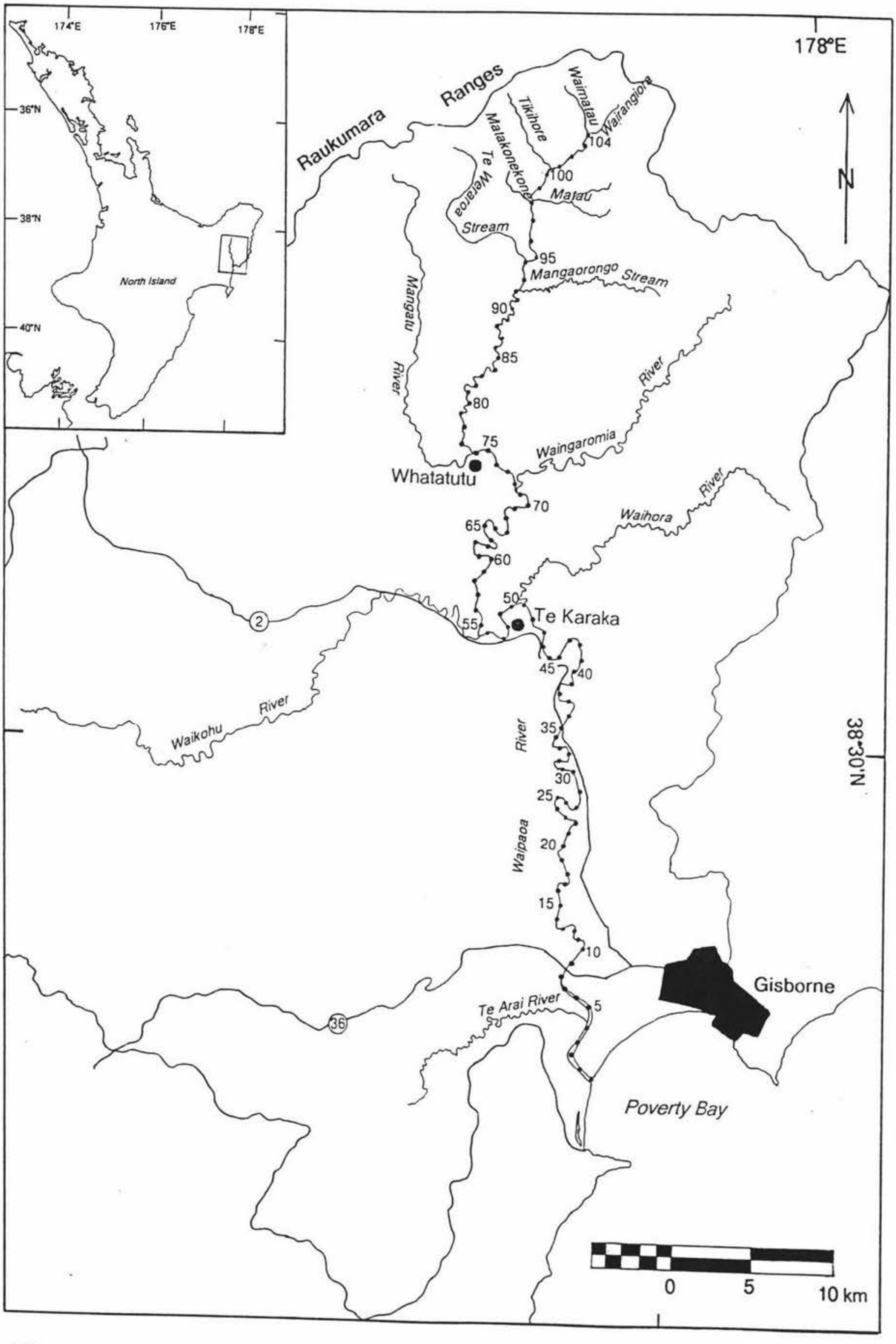


Figure 2.1 Location of the Waipaoa River, East Cape, New Zealand. The major tributaries and sampling sites in the Waipaoa River are also illustrated.

Figure 2.2 The upper braided reach of the Waipaoa River at high flow, overlooking the confluence with the Te Weraroa Stream, to the left. The Waipaoa River flows from the right (January 1996).

Figure 2..3 The middle reaches of the Waipaoa River at low flow, approximately 63 km upriver from the sea. The channel exhibits a tendency to braid at low flow, but at high flow is essentially single thread. The flow direction is from the top to the bottom of the photo (December 1996).

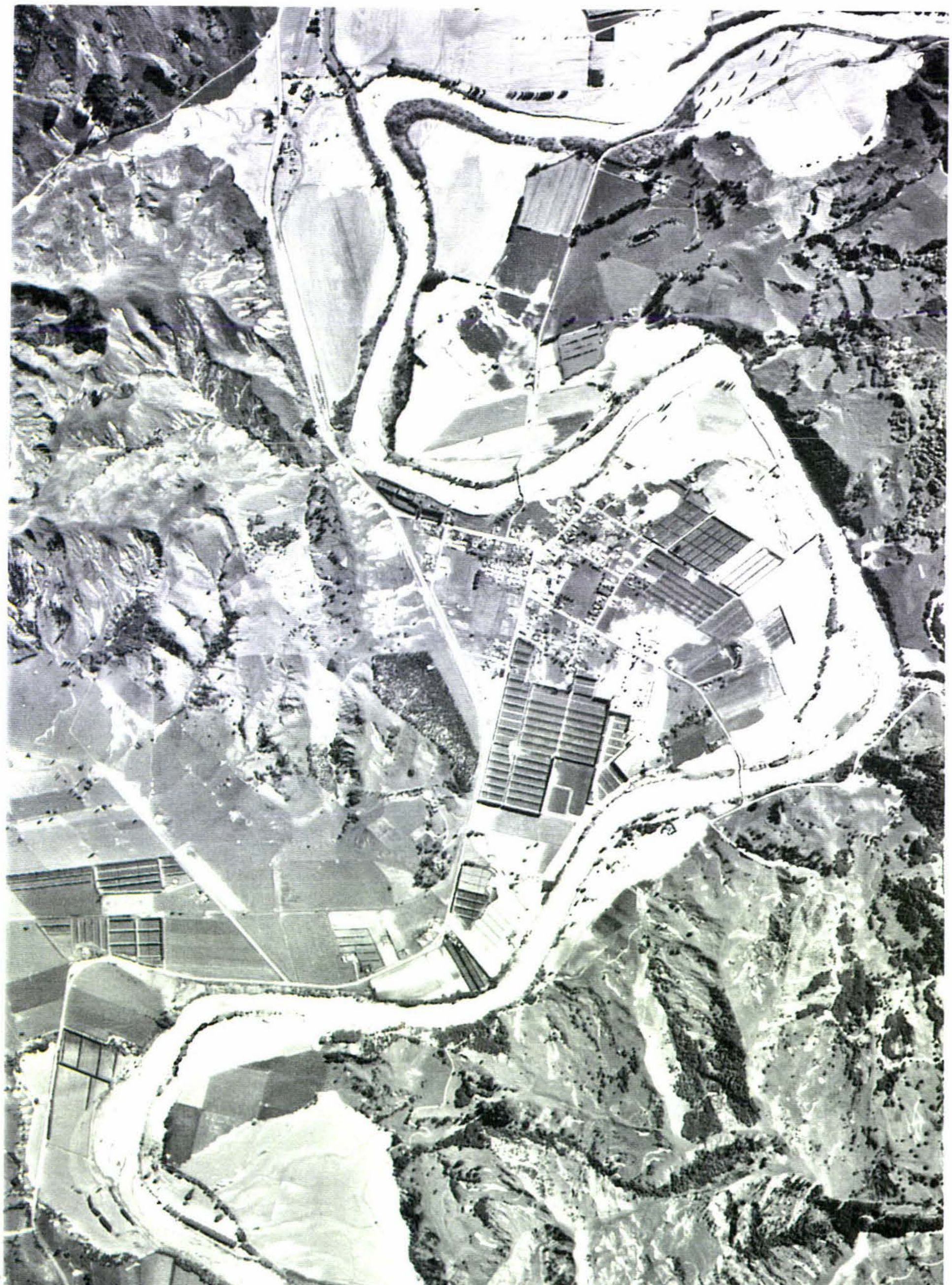


Figure 2.4 An aerial photo of the middle reaches of the Waipaoa River at Te Karaka (~50 km). The flow direction is from the top to the bottom of the photo. The river changes from a transitional to a meandering configuration near the bottom left corner (NZAM, March 1988).

Figure 2.5 The lower meandering reach of the Waipaoa River, at low flow. This photo illustrates the single thread configuration of the channel through the lower reaches (December 1996).

Figure 2.6 The sand-bed portion in the lower reaches in the Waipaoa River, at low flow and low tide. The photo was taken 2 km upriver from the coast (March 1996).

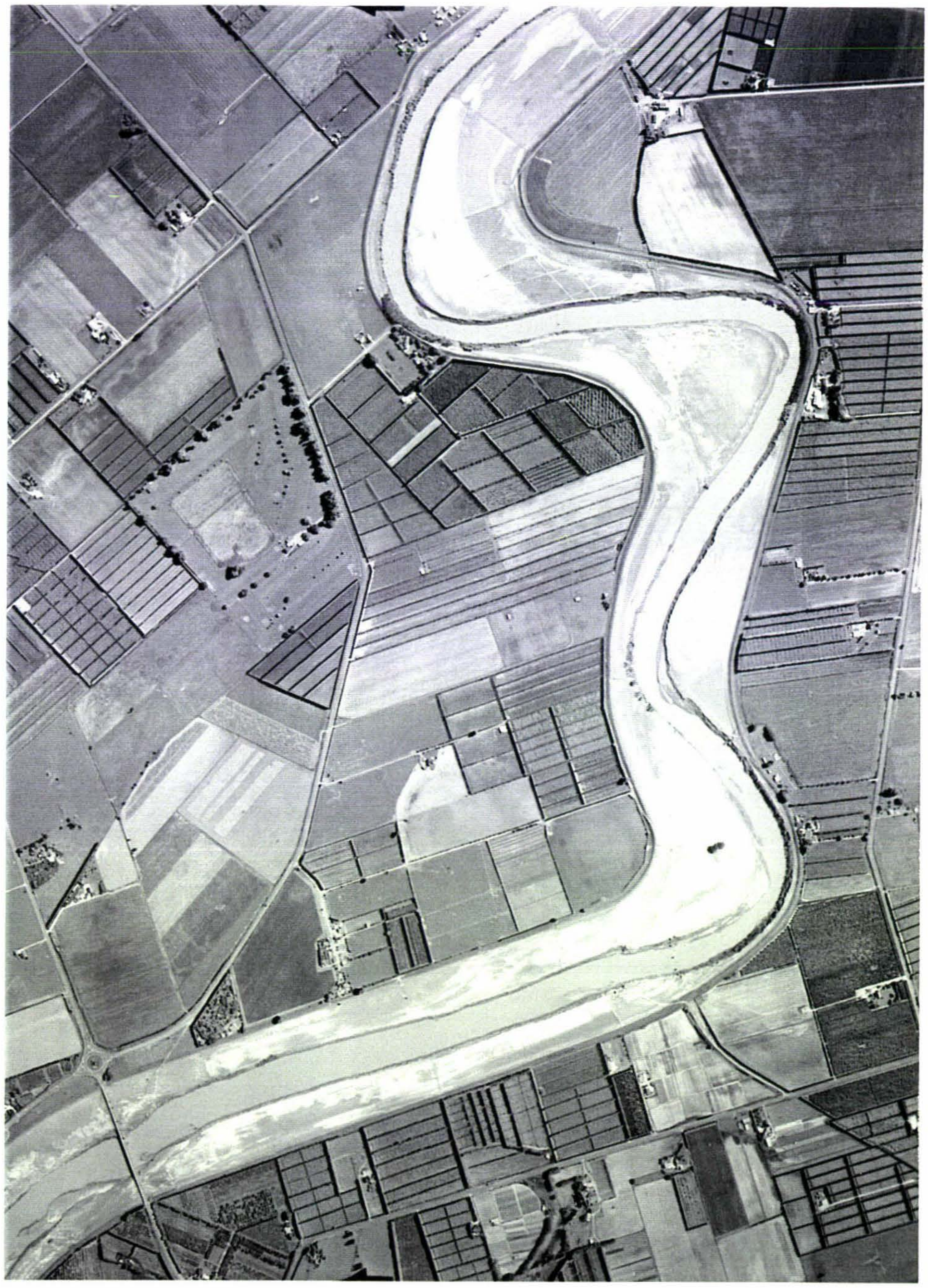


Figure 2.7 An aerial photo of the lower reaches of the Waipaoa River, illustrating the single-thread, meandering configuration of the channel. The gravel-sand transition occurs near the bottom of the photo, and the 9 km sampling site is located just upstream of the road bridge (NZAM, March 1988).

2.1 GEOLOGY

Sediment is supplied to the Waipaoa River from bank erosion along the length of the channel, as well as by tributary streams. The bulk of the Waipaoa's sediment load, however, is derived from the Upper Waipaoa and Mangatu catchments.

The Waipaoa catchment is located within a forearc basin; the accretionary wedge is situated offshore, and the frontal ridge occurs close to the axial Raukumara Ranges (Moore & Mazengarb, 1992). Subduction of the Pacific Plate beneath the Australian Plate, under New Zealand's East Cape region induces uplift rates of 3-4 mm yr^{-1} in the Raukumara Ranges, at the head of the Waipaoa River catchment (Mazengarb *et al.*, 1991). The rate of uplift declines towards the coast, and slight subsidence is experienced near the river mouth.

Sediments of the East Coast Allochthon and Motu Block underlie the catchment. Allochthonous strata structurally overlie Motu Block strata, and are separated from them by the Te Rata - Waitahaia fault zone; a low angle decollement fault that dips to the southeast, and is delimited as a zone of highly sheared rocks (Mazengarb *et al.*, 1991). The East Coast Allochthon consists of a series of displaced Cretaceous and Paleocene strata, bounded by thrust faults (Moore & Mazengarb, 1992). The thrust faults are manifest by bentonitic melange zones, consisting of highly crushed and sheared, argillite and mudstone. Sediments comprising the East Coast Allochthon probably were deposited in the Te Puia - Ruatoria area, and moved as a series of intact blocks to the south-west, during the early Miocene (Mazengarb *et al.*, 1991). The tightly folded, fractured, and intensely sheared rock units make the internal structure of allochthonous sediments very complex. Lithological formations include the Mangatu and Tikihore formations (Black, 1980).

Motu Block strata consist of Jurassic to Early Cretaceous 'basement' greywacke with a cover sequence of poorly consolidated Neogene (Miocene-Pliocene) shelf sediments. The low hills surrounding Gisborne and the Poverty Bay flats, and land in the eastern portion of the Upper Waipaoa catchment predominantly are underlain by sandstone, mudstone and alternating sandstone and mudstone of the Te Arai and Tokomaru formations (Black, 1980;

Mazengarb *et al.*, 1991). The spatial distribution of the main lithologies in the Waipaoa catchment are illustrated in Figure 2.8.

During emplacement of the East Coast Allochthon from the northeast, the Tikihore and Mangatu formations were folded and overturned along a dominant northwest trending axis (Mazengarb *et al.*, 1991). Motu Block sediments in the Waipaoa catchment are folded into simple anticlinal and synclinal structures. Major faults in the headwater region include the Te Weraroa, Te Waka, Waipaoa and Wheturau faults. These predominantly are northeast dipping, high angle thrust faults that trend in a southeast direction (Mazengarb *et al.*, 1991). The Upper Mangatu and Waipaoa catchments are divided into two major units by these four faults; Motu Block tertiary sediments lie to the east of the Waipaoa fault, and fault bounded blocks of the East Coast Allochthon lie to the west of the Waipaoa fault (Black, 1980).

Black (1980) divided the upper reaches of the Waipaoa and Mangatu Rivers into three geologically distinct subareas (Figure 2.9). The eastern flanks of the Raukumara Ranges delineate the northern-most extent of the North Island Axial ranges. The Tikihore and Waimatau catchments are underlain by upper Cretaceous to Paleocene sandstone, underlying the Raukumara ranges. Paleocene aged siltstone (argillite) and fine-grained marl underlie the Te Weraroa catchment. These units are part of the East Coast Allochthon, and as a consequence are highly crushed and sheared. The eastern flanks of the headwaters are underlain by gently dipping Miocene and Pliocene sediments, folded into the Tutamoe syncline.

Four lithological formations are present in the headwater region (Black, 1980). (i) The Tikihore Formation crops out in the Te Weraroa, Tikihore and Waimatau catchments north of the Tikihore fault block. It was deposited in a high energy, shallow marine, shelf environment, and consists of Upper Cretaceous sandstone and alternating carbonaceous siltstone, that often contains sandstone concretions. Basalt and volcanic conglomerate grading to sandstone also is present. (ii) The Upper Cretaceous to Eocene aged Mangatu Formation (synonomous with Whangai shale) also was deposited in a shallow marine, shelf environment. It conformably overlies the Tikihore Formation, and predominantly is

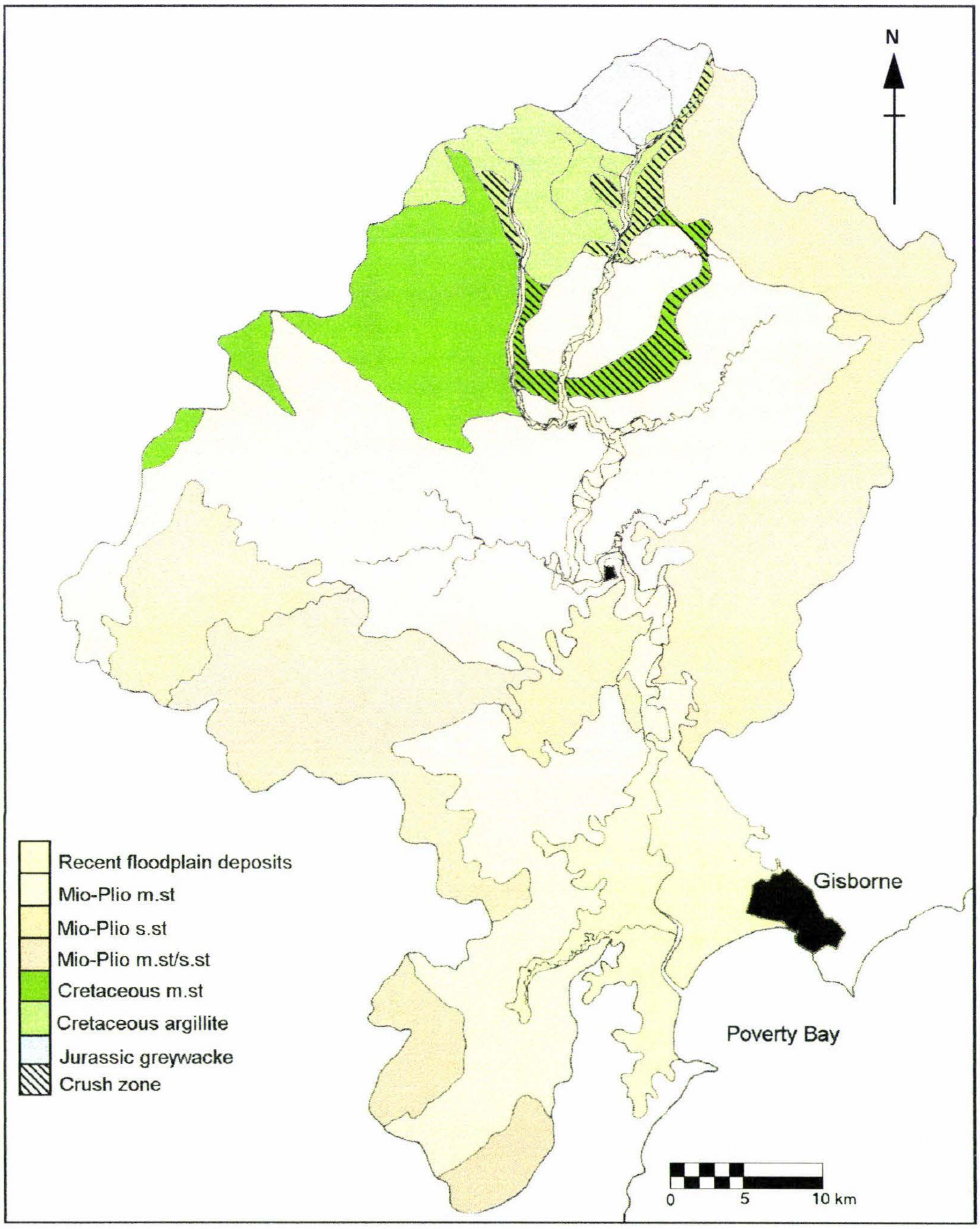


Figure 2.8 Generalised lithology map of the Waipaoa River catchment (modified from Mazengarb *et al.*, 1991).

composed of calcareous siltstone. Minor amounts of sandstone, glauconitic sandstone, black aromatic siltstone, marl and limestone also are present. Bentonitic mudstone typically is associated with the crush zones as well as major faults. The Mangatu Formation underlies the upper Mangatu, Te Weraroa and Matakonekone catchments, and also crops out along the Waipaoa River valley, as well as in the Wairangiora catchment. (iii) The Upper Miocene Te Arai Formation unconformably overlies the Mangatu Formation, and is dominated by mudstone lithofacies that include alternating sandy siltstone and fine grained sandstone strata. Minor amounts of mafic igneous conglomerate and coarse coquina limestone also are present. The Te Arai Formation crops out on the eastern side of the Upper Waipaoa and Wairangiora catchments, in the Mangaorongo Stream catchment, and through the gorge. The Te Arai Formation is equivalent to the Tolaga group lithofacies of Mazengarb *et al.* (1991). (iv) The top of the Tertiary sequence

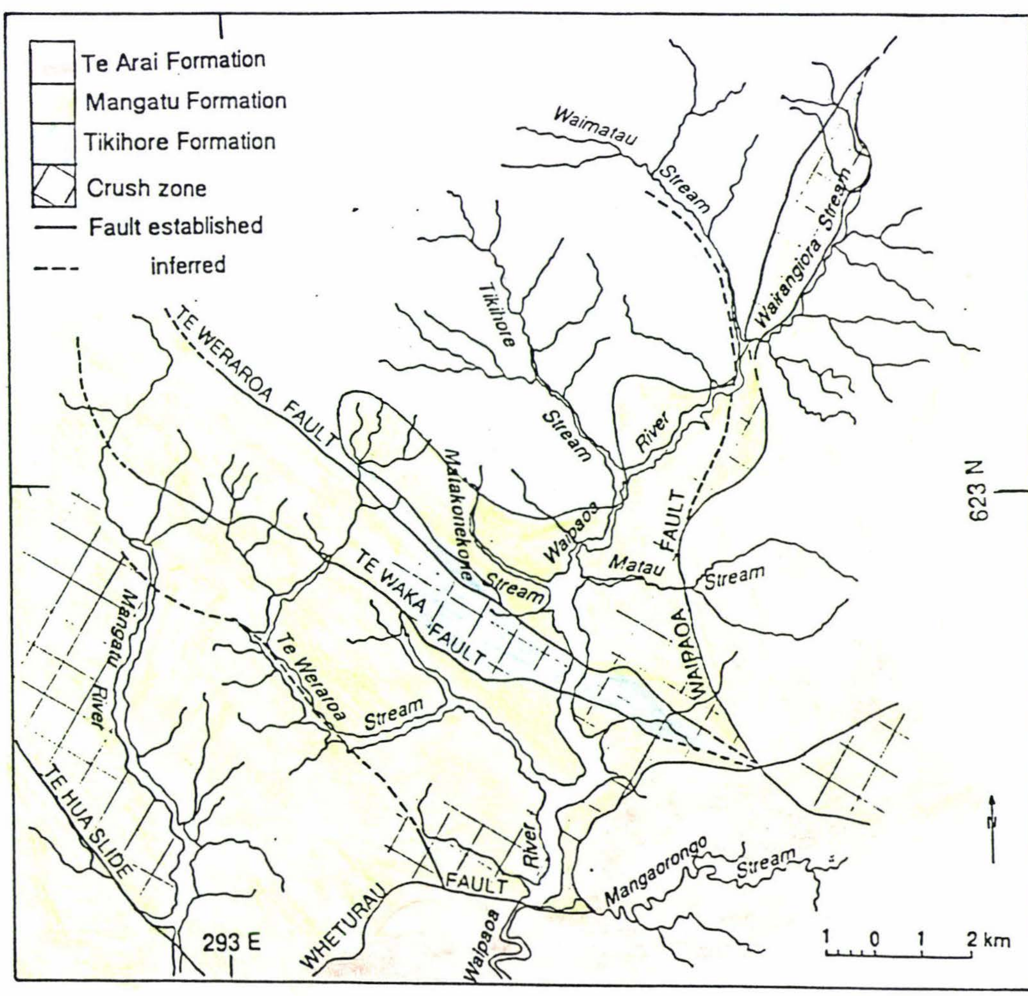


Figure 2.9 Major faults in the upper Waipaoa River catchment that divide the area into fault bound blocks (from Black, 1980).

in the headwaters of the Waipaoa River is represented by the Late Miocene Tokomaru Formation. It consists of massive blue-grey sandstone, deposited in a mid-shelf environment. The Tokomaru Formation unconformably overlies the Te Arai Formation.

2.2 GEOMORPHOLOGY

The various combinations of lithology, structure and topography in the upper reaches of the Waipaoa River have lead to the development of distinct landform combinations, that exhibit varying degrees of instability (Gage & Black, 1979). In general, the Cretaceous and Paleocene rocks underlying the majority of the upper catchment exhibit a greater susceptibility to erosion than the Tertiary rocks to the east, and southeast. The combination of structure, involving stratification, folding, faulting, joints, and fractures, with lithology, which includes the distinct mineralogical and hydrological properties of the Cretaceous-Paleocene rocks, has rendered these rocks highly susceptible to erosion (Gage & Black, 1979). Where the topography is steep, or the orientation of bedding planes is aligned parallel to the exposed hillslope, this susceptibility is enhanced. The Tertiary mudstone and sandstone units generally are more massively bedded and exhibit less joints and faults than the Cretaceous-Paleocene rocks, and therefore are less likely to exhibit such severe forms of erosion. As a consequence of this, different kinds of landforms, exhibiting varying degrees of instability have formed on the separate lithological formations of the Upper Waipaoa (Gage & Black, 1979). The upper reaches of the Tikihore and Waimatau streams are situated on the eastern flanks of the Raukumara Ranges. Characteristic landforms include steep hillslopes (>32 degrees) formed on well indurated alternating sandstone and siltstone (Moore & Mazengarb, 1992). Soil slips and deep seated earthflows are the dominant forms of erosion in these catchments, with some examples of severe gullying (Page, 1994).

Much of the Upper Waipaoa catchment, including the Waipaoa and TeWeraroa valleys, are characterised by steep hill slopes underlain by sandstone and siltstone (Moore & Mazengarb, 1992). Low hills underlain by bentonitic mudstone, exhibit extreme gully and earthflow erosion. Slopes exhibiting deep-seated earthflows, generally are long with hummocky surfaces, and often are undercut at the base by stream erosion. The erodible nature of these slopes is attributed to the high content of swelling clay (bentonitic clay) in the parent rock, and to the highly crushed nature of the units (Claridge, 1960). Some of the most conspicuous erosion occurs as large amphitheatre-like gully complexes (such as the Tarndale gully), that actively are contributing sediment to the river system (Banbury, 1996; DeRose *et al.*, in preparation).

The Waipaoa River catchment downriver from Waipaoa Station, and east of the allochthon in the headwaters, is predominantly composed of rolling hill country, underlain by the Te Arai and Tokomaru formations. Unique combinations of landforms and erosion types are associated with the different lithofacies within these formations (Page, 1994). Long steep hill slopes that characteristically exhibit scarps and bluffs are underlain by sandstone lithofacies. Erosion of cuesta and plateaux surfaces (e.g., such as the Tutamoe plateau), is slight to moderate. Massive siltstone, occurring predominantly in the Waihora catchment, has formed steep hill slopes that are prone to landsliding. In the Waingaromia catchment, as well as in the Waerenga-o-Kuri area, steep hill slopes underlain by loose jointed, crushed and sheared mudstone exhibit deep linear gullies, earthflows and slumps. Steep hill slopes also are associated with close jointed mudstone, which predominantly underlies the areas from Te Karaka to Whatatutu, Waihora, Te Arai and Ngatapa. Alternating mudstone and sandstone lithofacies occur predominantly to the west of the Waipaoa River, and are associated with very steep landslide prone hill slopes. Sandstone units have formed strike ridges and asymmetric cuesta where they are present (Moore and Mazengarb, 1982).

Between 92 km and 77 km in the Waipaoa River, a narrow gorge exists where the Waipaoa River has incised between high Pleistocene terraces and low hills that are underlain by Miocene mudstone and alternating mudstone and sandstone. The morphology of the river undergoes a marked change from a multiple-thread, braided channel, to a single-thread meandering channel at the upstream end of the gorge. Figure 2.10 illustrates the effect of the change in the underlying geology, coincident with the upstream end of the gorge, has on the Waipaoa River.

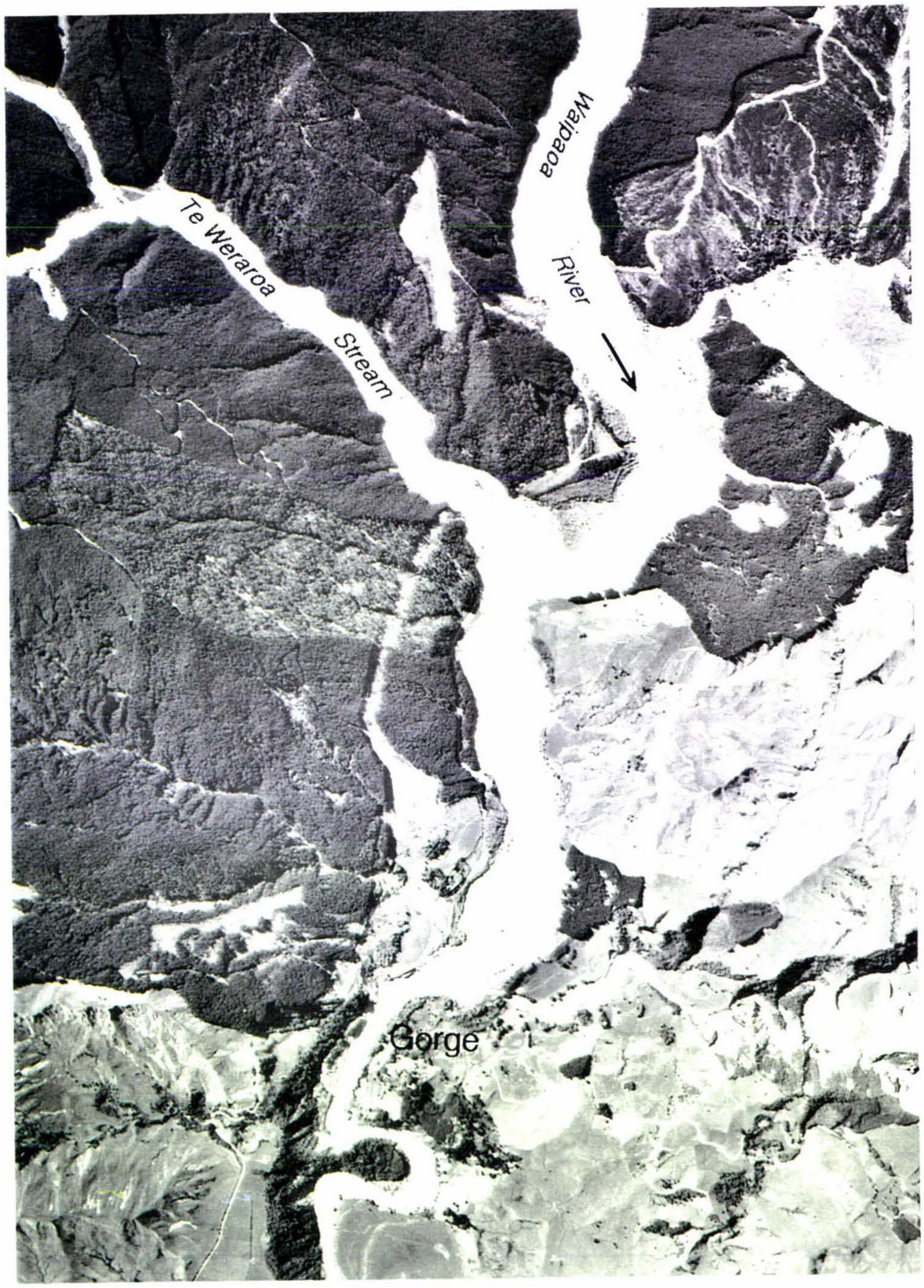


Figure 2.10 An aerial photo illustrating the change in width and channel planform pattern of the Waipaoa River at the boundary between Cretaceous and Miocene sediments at the upstream end of the gorge (NZAM, March 1988).

A simplified geological cross-section through the gorge, parallel to the general flow direction of the Waipaoa River, is presented in Figure 2.11. The Miocene mudstone of the Te Arai Formation sediments are separated from the Cretaceous sediments of the East Coast Allocthon by reverse thrust faults, and the mudstone appears to be down faulted against allocthonous sediments (Mazengarb *et al.*, 1991). This means that there is no apparent structural explanation for the existence of the gorge. Intuitively, a narrow gorge is not expected to form within relatively low strength sediments, such as the poorly consolidated mudstone underlying the gorge in the Waipaoa River. But, the occurrence of gorges, such as this, are a relatively common feature on the East Coast of the North Island, in situations in which allocthonous sediments are positioned directly adjacent to *in situ* sediments (Mazengarb, personal communication).

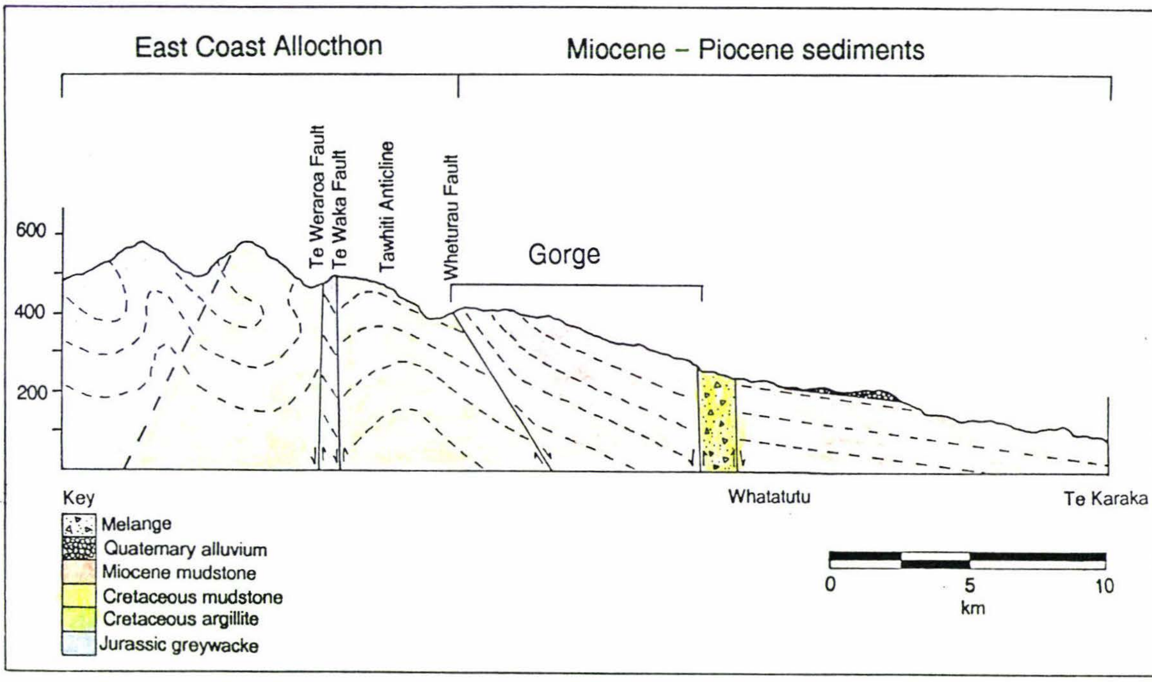


Figure 2.11 A generalised geological cross section through the gorge, parallel with the general flow direction of the Waipaoa River (modified from Mazengarb *et al.*, 1991).

The lithological boundary separating the allocthonous rocks from the Miocene mudstone is coincident with the top of the gorge; the East Coast Allochthon is situated upstream of the gorge, and the *in situ* mudstone is present through the gorge. The gorge exists due to the inherent differences in relative mass rock strength between the crushed and sheared rocks of the East Coast Allochthon, and the *in situ*, cemented Miocene mudstone. The Miocene mudstone is a relatively soft material and readily disintegrates when in contact with water, but as a rock mass, it exhibits greater strength than the mass rock strength of the allochthonous sediments (Mazengarb, personal communication 1996). The presence of relatively harder bedrock has possibly prevented the river from widening, and braiding through this reach. The gorge opens up at the downstream end at the lithological boundary between the mudstone and melange formed during the emplacement of the East Coast Allochthon in Early Miocene times. Downstream of this point, the Waipaoa River has incised between high Pleistocene terraces and low hills, predominantly underlain by Miocene and Pliocene sediments, but it exhibits a considerably wider floodplain with various levels of Holocene and Recent river terraces adjacent to the river.

The Late Pleistocene to Holocene Poverty Bay Flats extend from the coast inland to Te Karaka. The area occupied by the flats is approximately 23 000 ha, or 10.5 % of the total Waipaoa catchment area (Page, 1994). The present day shoreline at the mouth of the Waipaoa River has prograded 11-12 km since the post-glacial sea level maxima 6.5 thousand years ago (Brown, 1994). The rate of seaward progradation of the shoreline was 0.2-0.8 m yr^{-1} over the last 1800 yrs, but the rate increased to 2.8 m yr-1 before 1910, due to deforestation in the headwater region at the end of the last century, and the subsequent influx of sediment to the river system (Brown, 1994). Maximum rates of shoreline progradation were experienced near the Waipaoa River mouth, which has changed position several times since European settlement. In 1946, the Waipaoa River was diverted from near Young Nicks Head to the present position of the river mouth by a groyne, which has prevented further migration of the river mouth.

Prominent Late Pleistocene river terraces are present along the Waipaoa and Mangatu Rivers in the vicinity of Whatatutu, and in the Upper Waipaoa River catchment. The terraces are composed of alluvial gravel, sand and silt, and are generally mantled by tephra. The terraces commonly are lie > 60 m above the present river level (Mazengarb *et al.*, 1991).

2.3 VEGETATION & EROSION HISTORY

The contemporary vegetation cover of the Waipaoa catchment consists largely of pasture (77 %) and exotic (non-native) forest (13 %) (Page, 1994). Soils of the Poverty Bay Flats are utilised for intensive horticultural and cropping purposes (2.5 %). Most of the low coastal hills, and the hill country surrounding the Poverty Bay Flats are in pasture. Exotic forest covers much of the steep, headwater regions of the Waipaoa River. Substantial areas of steep erodible hill country still remain in pasture, and only a small percentage of original native forest now remains (2.5 %). The remaining 5% of the catchment is accounted for by secondary forest or scrub, kanuka/manuka, and bare ground (Page, 1994).

Maori settlement in the Waipaoa catchment dates from ~800 years before present (BP) (Jones, 1988). The Maori settlements predominantly were situated in the southwest portion of the Poverty bay flats, and along the banks of the Waipaoa River. Principal areas of settlement prior to 350 years BP were at Maraetaha, Manutuke, Repongaere, Waituhi, Waerenga-a-hika, and Kaitaratahi (Jones, 1988).

At the time of European settlement in the 1830's, most of the catchment was forested (Jones & Howie, 1970). The floodplain consisted of kahikatea forest intermixed with puketea, tawa, titoki, puriri, matai and totara. In the headwaters the forest consisted of podocarp and mixed broadleaf forest, with beech on the higher hills. Manuka and kanuka were present on cleared sites, and along the banks of the Waipaoa and Mangatu rivers (Jones & Howie, 1970). Forest clearance in the Waipaoa River catchment began at Bushmere (near the coast) in the 1830's, and during the period 1830 to 1880, most of the land on the Poverty Bay flats was cleared and fenced (Pullar, 1962). The area devoted to settlement expanded rapidly from 1871 to 1875, at which time hillslopes surrounding the floodplain were cleared. In the period 1890 to 1910, deforestation intensified in the headwater areas of the Waipaoa and Mangatu Rivers. In these areas the forest was cleared by burning (Howard, 1976). The majority of the upper catchment was cleared by 1910 (Allsop, 1973).

In an area already predisposed to erosion as a result of the combination of geology, structure and tectonics, rapid forest clearance caused widespread and severe soil erosion throughout the upper Waipaoa River catchment (Akehurst, 1963). The sediment was fed into the channels of the Waipaoa River system, which aggraded, and in the upper reaches, changed from a single to a multi-thread configuration. The first morphologic changes to the river channel were observed early in the 20th century, when the Waipaoa River channel changed from a 'hard bed with large boulders' to a 'soft boggy bottom' (Jones & Howie, 1970). Streams throughout the catchment already had begun to aggrade prior to the turn of the century. In the headwaters, several homesteads built on low terraces beside the river had to be moved to higher ground, the sites they once occupied are now part of the active river channel (Jones & Howie, 1970).

The Gisborne District Council (GDC; formerly the Poverty Bay Catchment Board), in 1947, began regular cross section surveys at 1 mile (1.6 km) intervals along the main channel, that have continued until the present day. This record is unique for a river of this size. The cross section data show that >32 million cubic metres of material was deposited in the Waipaoa channel during the period 1948-1979. The highest rates of aggradation occur in the Upper Waipaoa and Te Weraroa catchments (Hosking, 1985).

During the 1960's, in an effort to stabilise hill slope erosion, the most severely eroded land in the headwaters was afforested. In the period 1960 to 1971, 5400 ha of land within the headwater reaches was planted, predominantly with tree species such as Radiata pine, Douglas fir, and Corsican pine (Allsop, 1973). Once the forest was established (in the 1970's) the rate at which sediment was supplied to the channels declined. Cumulative sediment accumulation rates for each major reach are shown in Figure 2.12. The decrease in sediment storage is readily apparent, with the upstream reaches exhibiting the greatest decline (Hosking, 1985). Aggradation has continued in Te Weraroa Stream, but it has declined at an exponential rate since 1948 (Banbury, 1996). The decline in sediment storage was reflected in three time periods; 1948-1961, 1961-1975, and 1975-1996 (Banbury, 1996). Aggradation was the most rapid from 1948-1961, as a result of deforestation and increased storm frequency. From 1961-1975 the rate of aggradation declined, however, it was still the dominant process occurring in the stream. The decline in aggradation rate was attributed to the decreased storm frequency (and therefore decreased sediment generating and supply events) (Banbury, 1996). Reforestation was not considered to have affected aggradation in this time period. The rate of aggradation decreased further in the period 1975-1996, and was attributed to the establishment of the forest cover and canopy closure. In this time period some reaches of the Te Weraroa were still aggrading, while others obtained equilibrium, or were degrading (Banbury, 1996).

Banbury (1996) also determined that the greatest rates of aggradation occurred in the reaches that were in close proximity to sediment sources, and that the primary source of the sediment was from gully erosion.

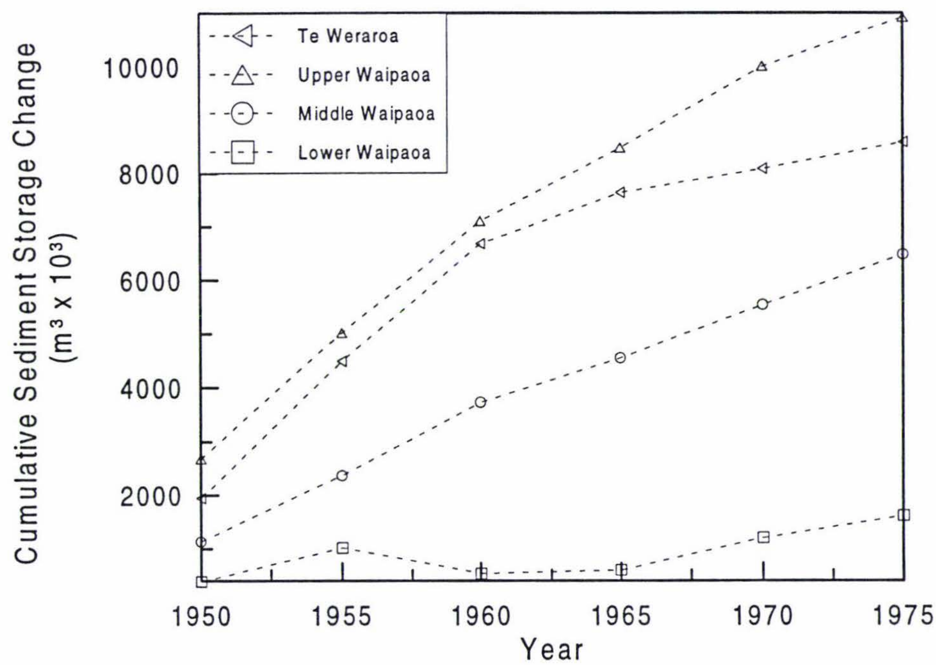


Figure 2.12 Sediment storage change for each major reach of the Waipaoa River, and for the Te Weraroa Stream. (Data source: Hosking, 1985).

A similar decline in sediment production rates from the gully complexes within the Te Weraroa and Mangatu catchments recently has been documented by DeRose *et al.* (in preparation). Sediment production rates from gullies within a 4 km^2 area were highest in the period 1939 to 1958, during which time the gullies underwent rapid expansion, resulting in a sediment production rate of 9.8×10^8 kg yr^{-1}. In the period 1958 to 1992 the rate of sediment production declined to 6.3×10^8 kg yr^{-1}. DeRose *et al.* (in preparation) concluded that the greater proportion of the sediment produced by gully erosion now enters the channel systems of the Te Weraroa Stream and the Mangatu River, and only a small portion is stored in the alluvial fan systems. Banbury (1996) also concluded that the amount of in-channel sediment storage in the Te Weraroa Stream was minor compared with the amount that was transferred to the Waipaoa River channel.

Declining sediment accumulation rates (Hosking, 1985; Banbury, 1996) and sediment production rates (DeRose *et al.*, 1997), most likely are due to the effects of reforestation, and the stabilisation of hill slopes. However, the decline in sediment production and storage also may be attributed to the dearth of large storms experienced in the period from the 1960's to 1988 (Banbury, 1996). Considerable aggradation of the Upper Waipaoa River was occasioned during Cyclone Bola, March 1988 (Peacock, 1991).

The decline in sediment production and storage in the headwaters that was experienced following reforestation (Banbury, 1996; DeRose *et al.*, in preparation) has not yet been matched in the middle and lower reaches of the Waipaoa River, which continue to aggrade. This is of concern for the maintenance of the flood control scheme protecting the Poverty Bay flats, and Gisborne City. The rising bed levels continue to reduce the capacity of the scheme, thus increasing the risk of flooding.

The lower 38.5 km of the Waipaoa River are part of the Waipaoa River Flood Control Scheme. The scheme consists of 38.5 km of stopbanks on either side of the river, from the mouth to Raupuke, three diversions at Te Wairau, Matawhero and Teitjens, and a floodway at McPhails bend (31-33 km). Construction of the flood control scheme began in 1953, and was finally completed in 1973 with the raising of the Waerenga-a-Hika spillway. During the twenty year period, the river downstream of Brown Rd (now 20 km) was shortened by a total length of 8 km. This shortening of the channel has increased the average gradient of the river, and promoted general degradation of the channel from this point to the sea (Hosking, 1985). The flood control scheme initially was designed to provide protection from a 5300 $m^3 s^{-1}$ flood with a return period of approximately 100 years (Todd, 1964).

Aggradation of the bed and sedimentation on the berms and banks has resulted in a 10% loss in scheme capacity (~500 $m^3 s^{-1}$) between 1979 and 1990 (Peacock, 1991). This has resulted in a decrease in the return period of bank overtopping floods, at the 19 M cross section (~23 km), from 90 years in 1979, 60 years in 1990, to a predicted 35 years in the year 2015 (Peacock, 1991).

2.4 CLIMATE & HYDROLOGY

The Waipaoa River catchment experiences a humid temperate climate. The rainfall received by the Waipaoa catchment can be highly variable, but generally ranges from 1000 mm yr^{-1} at the coast to over 3000 mm yr^{-1} in the upper catchment (Smith 1977; Thompson, 1987). The rainfall gradient is topographically controlled, so the highest rainfall is experienced in the headwaters, in the north-west portion of the catchment. Heavy rainfalls over the entire catchment are associated with depressions moving in a south-easterly direction across the North Island. In this situation, rainfall in the convergence zone is intensified by orographic uplift due to easterly winds (Hessell, 1980).

The Waipaoa River is well known in New Zealand for its very high suspended sediment yield of ~6 000 t km^{-2} yr^{-1} (Griffiths, 1982). Individual subcatchments generate suspended sediment yields as high as 14 000 t km^{-2} yr^{-1}, (e.g., Waingaromia and Mangaorongo streams), where the underlying geology is dominated by poorly consolidated Miocene mudstone and siltstone). The mean annual discharge of the Waipaoa River measured at Kanakania is 35 m^3 s^{-1}. Seventy-five percent of the total catchment area is upstream of the gauging station at Kanakania. Low flow mean discharge during summer and winter is 10 m^3 s^{-1} and 15-20 m^3 s^{-1} respectively. The stage-discharge relationship for the Waipaoa River, measured at Kanakania, is shown in Figure 2.13. The 1.5 year flood is approximately 1000 m^3 s^{-1}, and the largest recorded flood was Cyclone Bola, in March 1988, with a peak discharge of 5300 m^3 s^{-1} and a return period of approximately 100 years.

The Waipaoa River has a long history of devastating floods. The last major flood was Cyclone Bola, which occurred in March, 1988. The tropical cyclone lasted three days, during which time some areas in the Waipaoa catchment received ~900 mm of rain (Singleton *et al.*, 1988). The Waipaoa River reached its highest ever recorded level about 48 hours after the storm began. Although the Waipaoa River Flood Control Scheme initially was designed to cope with a flood of this magnitude, the stop banks were overtopped in several places, inundating large areas of the Poverty Bay flats (Peacock, personal communication 1996). Most of the land on the flats is intensively utilized for horticultural and cropping purposes, thus damage due to sedimentation was great.

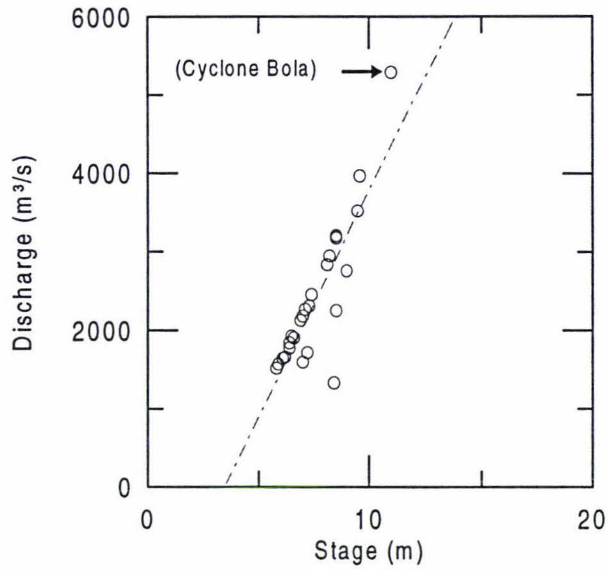


Figure 2.13 Stage-discharge relationship for the Waipaoa River at Kanakania (48 km). The equation describing the relationship is $Y = 577.4*X-1992.2$ ($R^2 = 0.75$).

3.1 REVIEW OF SEDIMENT SAMPLING TECHNIQUES

The sampling of coarse fluvial sediments in a representative and accurate manner is a topic that has received much attention (e.g., Kellerhals & Bray, 1971; Hey & Thorne, 1983; Church *et al*, 1987; Wolcott & Church, 1991; Diplas & Fripp, 1992; Marcus *et al*, 1995; and many others). There are two principal approaches to sampling coarse fluvial sediments: subsurface and surface sampling.

Subsurface samples are collected by a volumetric or bulk sampling technique. A predetermined volume of material is excavated from the river bed. In most cases, the surface layer is removed prior to the removal of subsurface material. Surface sediment sampling involves the removal of the sediment exposed on the bed surface. The surface sediment size is important because it affects resistance to the flow, and because bedload is drawn from the bed surface (Dietrich *et al*, 1989). Surface particles thus constitute particles that may be directly entrained by the flow (Diplas & Sutherland, 1988). The surface layer, which is typically coarser than the underlying material, is one grain diameter thick (Parker, 1991a). Volumetric sampling cannot be used when one dimension of the sample is comparable to the size of the constituent particles (Ettema, 1984). Various methods have been proposed for the collection of surface samples, and include areal, transect, and grid sampling (Kellerhals & Bray, 1971).

Subsurface sampling: Volumetric sampling involves excavating a predetermined volume of material from the river bed. The sample then is subject to sieve analysis using square mesh sieves. Size class data either are expressed on a frequency-by-weight, or a volume-by-weight basis (Kellerhals & Bray, 1971; Diplas & Sutherland, 1988). To obtain a representative volumetric sample, the volume of sediment collected must be large enough to ensure that it is independent of individual particle dimensions, and the sample is not biased towards any particular grain size fraction (Diplas & Sutherland, 1988; Diplas & Fripp, 1992). A sample is deemed to be representative if repeated sampling of the same deposit yields similar results (Church et al, 1987). DeVries (1971) and Church *et al.* (1987) addressed the question of the amount of material that is required to ensure a sample is representative.

Sample size standards are often based on the largest particle diameter (expressed in terms of a particles intermediate (b) axis) in the sample. This is because the largest particles are the least well represented, and should determine the sample size (Church *et al.*, 1987). Particle mass, however, increases in proportion to particle volume (D^3), rather than diameter (DeVries, 1971). Sampling standards based on particle diameter therefore are likely to underestimate the actual required sample size (Gale & Hoare, 1992). DeVries (1971) proposed sample sizes that are based on the weight of the largest particle. The results of the analyses of bed material samples are subject to systematic and random errors (DeVries, 1971). DeVries (1971) determined the level of accuracy that was required to ensure that the error associated with each particle size fraction was acceptable. High accuracy is achieved when the weight of the largest particle is <1 % of the total sample weight, medium accuracy when the weight of the largest particle is <3 % of the total sample weight, and low accuracy when the weight of the largest particle is <10 % of the total sample weight.

Church *et al.* (1987) suggest that a sample will provide an adequate representation of the population from which it was drawn, if the weight of the largest particle is <0.1 % of the total sample weight. Diplas and Fripp (1992) argued that the minimum weight of a volumetric sample corresponds to a sample size in which the largest particle is between 0.1-0.5 % of the sample weight. The relation between the intermediate axis of largest particle and the specific weight of the material was used to derive the required weight. Mosely and Tindale (1985) concluded that a sample where the largest particle represents < 5% of total sample weight or volume is acceptable, for most practical situations, and will produce an unbiased estimate of the mean particle size.

The chosen sampling weight also should balance the sample size required for a volumetrically representative sample, with the requirement that the sample is representative of a particular sedimentologic and geomorphic provenence (Dunkerley, 1994). Wolcott and Church (1991) proposed that the proportion of each facies present could be weighted to the proportion it occupies in the study area.

Surface sampling: Three principal methods are used to determine the particle size distribution of surface sediments: areal sampling; transect sampling; and grid sampling. Areal sampling involves removing all the particles exposed on the surface that lie within a predetermined area. The particles to be removed may be sprayed with paint and collected manually. Wax or another adhesive medium also may be used to remove the surface particles. Vertical photographs of the bed also constitute an areal sample (Kellerhals & Bray, 1971). Transect sampling involves collecting all the particles lying beneath evenly spaced points along a transect line laid out across the sampling area (Diplas & Sutherland, 1988). Grid sampling involves establishing a grid on the surface of the river bed. The particles beneath each grid point are collected and constitute the sample (Kellerhals & Bray, 1971). Wolman (1954) proposed a variation on the grid method which involves randomly walking over the bed surface. After each successive step, the particle directly beneath the toe of one's boot is picked up. A Wolman sample conventionally involves the collection of 100 particles.

Particle size statistics obtained by grid sampling and by the Wolman method produce statistically indistinguishable particle size parameters (e.g., D_{50} and D_{84}), provided a single operator performs all the counts (Marcus *et al.*, 1995; Wohl *et al.*, 1996). However, clast selection is biased towards larger particles. This is because larger particles occupy a greater surface area than smaller particles. Both methods, however, are spatially independent and random (Wohl *et al.*, 1996). Bias associated with grid samples can be reduced or eliminated by employing a grid spacing several times larger than the largest particle exposed on the bed surface (Fraccarollo & Marlon, 1995). The size of the particles that have been collected is expressed as a linear dimension (Kellerhals & Bray, 1971). The intermediate axis of a particle typically is used for this purpose. The frequency of particles in each size class is expressed either as percentage by weight of the original sample (as in conventional bulk sieve analysis), or as percentage by number of the total number of particles in a sample.

The sampling method ultimately is governed by the purpose of the investigation, and conditions in the channel in question (Wolcott & Church, 1991; Wohl *et al*, 1996). For example, investigations concerned with the initiation of sediment transport or channel roughness will focus on the surface layer, (e.g., Clifford *et al.*, 1993). The sampling technique also should produce results that are comparable with those generated by other procedures, and should be efficient in terms of time and resources (Kellerhals & Bray, 1971).

Laboratory and field studies of fluvial sedimentology have traditionally utilized volumetric samples that are analysed by sieving (Kellerhals & Bray, 1971). Ideally, the sampling procedure chosen should be equivalent to bulk sieve analysis, or produce results that may be converted to yield equivalent results, to enable comparisons between samples. Equivalent sampling techniques are those that, on average, produce identical particle size distributions when applied to the same deposit (Kellerhals & Bray, 1971).

The only method of surface sampling that is directly comparable (equivalent) to bulk sieve analysis is grid-by-number sampling (Kellerhals & Bray, 1971). The volume of a bulk sample is independent of particle dimensions (predetermined), but the volume of a grid sample depends on all three particle dimensions. To convert a bulk sample to its grid-by-number equivalent requires a weighting factor of $1/D^3$. To convert grid-by-number to its frequency-by-weight equivalent, a weighting factor of D^3 is required. By combining the two weighting factors, D^3 cancels out. The grid-by-number technique is therefore directly comparable to the frequency-by-weight method of bulk sampling, and is expected to produce the same particle size distribution, providing the same sediment population is sampled.

The proportion of sediment in each size class of the particle size distribution are influenced by the amount of all sizes present in the sample (Church *et al.*, 1987). The particle size distribution therefore should be restricted to the portion of the sediment population that is sampled representatively. Surface samples can be truncated at a lower size limit, below which removal and measurement of individual particles becomes impractical. The lower size limit usually is given between 2 and 8 mm (Wolman, 1954). Comparison between surface and subsurface samples requires that all samples are truncated at the same lower size limit (Church *et al.*, 1987).

Surface and subsurface sampling techniques differ due to the volume dimensions that are predetermined by the sampling method employed. Kellerhals & Bray (1971) devised a model to convert from one sampling technique to another on the basis that frequency-by-number and frequency-by-weight samples differ by a factor of D^3, plus the number of predetermined dimensions. Conversion factors for each size interval (I) are calculated by:

$$f_{ci} = f_{di}\, D_{gi}^{\ x} / \{ \sum_{I=1}^{n} f_{di}\, D_{gi}^{\ x} \} \qquad (3.1)$$

where f_{di} is the observed proportion of sample in the ith size class with a mean size of D_{gi}; x is the dimension required for conversion (determined by technique); n is the number of size classes; and f_{ci} represents the converted proportions (from Church *et al*, 1987).

Criticism of Kellerhals and Bray's model (1971) has arisen because it does not always correctly compensate for the presence of fine material (Gomez, 1983; Church *et al.*, 1987). Gomez (1983) and Diplas and Sutherland (1988), amongst others, have highlighted the need for a conversion factor which accounts for packing, void spaces and particle exposure, which are ignored by the Kellerhals and Bray (1971) model. Gomez (1983) suggests that a value of x = -0.5 may be appropriate for converting an area-by-weight sample to its volume-by-weight equivalent. Both the original cube model (Kellerhals & Bray, 1971) and the modified cube model put forward by Diplas and Sutherland (1988) produce identical results for grid and transect surface sampling techniques. This arises because all particles in a grid or transect sample originate solely from the top layer of the bed surface.

Fraccarollo and Marlon (1995) also criticize Kellerhals and Bray's (1971) conversion model. They argue that the cube model used by Kellerhals and Bray (1971), and the modified cube model proposed by Diplas and Sutherland (1988), are not representative of the arrangement of particles in real coarse sediment mixtures. The conversion model proposed by Fraccarollo and Marlon (1995) places no restrictions on the number of size fractions, or on the size, shape and arrangement of the constituent particles. Separate models were proposed for matrix supported and framework support sediment mixtures.

To test Kellerhals and Bray's (1971) conversion model, Church *et al.* (1987) took repeated grid and areal samples from the surface of a sediment mixture with a known particle size distribution. Their results indicate that the conversion procedures are appropriate, and support the use of the Kellerhals and Bray (1971) conversion model. Diplas and Sutherland (1988) also reaffirmed the equivalence of the grid-by-number and volume-by-weight sampling methods.

3.2 Bed Material Sampling in the Waipaoa River

The Waipaoa River is aggrading. Cross section data obtained over the last 50 years indicate that the rate of aggradation increases upstream from the sea to the headwaters. The fastest rates of bed level aggradation were experienced in the 1950's and 1960's, and the rate of aggradation has slowed appreciably within the last decade (Hosking, 1985).

To investigate the transfer of coarse fluvial sediment through the Waipaoa River system and to characterise the size of the mobile material, bed material samples were obtained from exposed bar surfaces at 1 km intervals along the channel from the confluence of Waimatau and Wairangiora streams to the sea; a distance of 104 km. The samples were obtained at low flow, as close to the centerline of the channel as possible. Sampling locations included the exposed surface of point, alternating and braid bars in curved, straight and braided reaches. Sampling was carried out during the summer of 1995/1996. The sampling sites were designated on topographic maps, but the exact location of each site was constrained by the local bed topography. In most cases sampling was accomplished within 100 metres of the designated location. No attempt was made to restrict sampling to a specific topographic or sedimentologic provenence. Sediment samples also were obtained from tributary channels, 1-2 km upstream from their confluence with the Waipaoa River, as well as from mass movements, gullies, bluffs, and banks that supplied sediment directly to the channel system.

Three sediment sampling methods were employed in the present study: Bulk sampling was employed to characterise the subsurface sediments; the surface sediments were characterised by grid-by-number sampling, supplemented by Wolman sampling.

Bulk sampling: Bulk sieve analysis was chosen as the most appropriate method of characterising the subsurface bed material. At each sampling site the surface layer within a 1 m^2 area was scraped off, and a 50 kg sample of the underlying substrate was removed with a shovel. The 50 kg sample weight was large enough to ensure that the weight of the largest particle was generally less than 2 % of the total sample weight, in accordance with the recommendations of Church *et al.* (1987). In no case was the weight of the largest particle greater than 5% of the total sample weight. The 50 kg weight also ensured that the subsurface bed material samples were not biased towards toward any particular particle size fraction.

The sample was passed through a 16 mm sieve in the field and all material >16 mm was retained. The <16 mm fraction was quartered and subdivided until a 3-4 kg subsample remained. This 3-4 kg subsample was retained for further laboratory analysis. The 4-3 kg subsample weight also ensured that the <16 mm subsample was not biased towards any particular particle size fraction.

***Grid-by-number sampling*:** Grid-by-number samples were obtained between 104 - 93 km in the Waipaoa River, using the Wolman (1954) method. Grid-by-number sampling was chosen as the most appropriate method for characterising the surface bed material population in the Waipaoa River because it is the only surface sampling technique that yields results that are directly comparable to the results obtained from bulk sieve analysis. A total of 100 pebbles were collected from the bed surface at each sampling site (in the same vicinity as the bulk samples were taken from, except for 103 and 104 km, at which no bulk samples were obtained). The b-axis of each pebble was measured to the nearest mm and the lithology noted. The coarse nature of bed material sediments in this reach prevented the representative use of bulk sampling, requiring sample sizes that were impractical to collect. For this reason, particle size statistics obtained from bulk sampling in the upper 5-6 km may underestimate the coarseness of bed material, due to the exclusion of very large particles from the bulk samples.

Additional grid-by-number samples were obtained at some 35 sites between 75 and 5 km. Only bar surfaces that exhibited armour development were sampled. A 2.1 m x 2.1 m grid, constructed of wood and string, was laid out on the bed surface (Figure 3.1). The grid had a spacing of 10 cm, and ensured that sample selection bias was eliminated. The particles on the bed surface directly beneath the grid intersections were collected. In situations where more than one particle was beneath the intersection, the top particle only was removed. Particles smaller than 3 mm were disregarded. Removal and measurement of particles smaller than 3 mm in diameter was considered impractical.

Figure 3.1 Positioning of the sampling grid on the bed surface of the Waipaoa River, at 28 km.

A high proportion of bar surfaces were overlain by sand or mud drapes which had accumulated during the falling stages of a previous flood. Miall (1996) referred to similar deposits as supra-platform deposits. No attempt was made to estimate the proportion of armoured vs. sand and mud covered surface at a sampling site. When grid sampling, armoured surfaces only were considered. Consequently, the grid-by-number samples may not be representative of the bar surface as a whole (or the reach), although, the grid-by-number samples are representative of the specific armour layer investigated.

Imbricated bar surfaces were not encountered in the Waipaoa River. The formation of imbricated surfaces probably was prevented by the high proportion of fine material, and the relatively small particle size (generally <45 mm). Imbricated surfaces are characterised by upstream dipping, disc or bladed particles, that generally exhibit intermediate axes >60 mm (Laronne & Carson, 1976). The formation of imbricated surfaces is explained by the rolling and sliding motion of the coarsest particles of the bed load. Pebbles smaller than 60 mm often are transported by saltation in coarse grained channels, and are not expected to produce such structures (Laronne & Carson, 1976).

3.3 Laboratory Analysis

In the laboratory, material >16 mm was passed through ½-*phi* interval steel mesh sieves. Every fifth >16 mm sample (*ie.* every five kilometres) was separated into its constituent lithologies (sandstone, siltstone, argillite, etc.) and the number of particles of each lithology noted. The short (a), intermediate (b), and long (c) axes of over 4000 pebbles were measured with calipers, from 20 sampling sites along the Waipaoa River. Pebble axis measurements were obtained from a sample of ~ 50 randomly selected particles of each lithology, in each particle size fraction. The intermediate (b) axis of each particle obtained by grid-by-number sampling was measured to the nearest mm with calipers.

Each <16 mm subsample was weighed wet and air-dried. The dry samples were reweighed, and net wet to dry conversion factors were defined on the basis of this data. Particle aggregates were broken up using a stiff paintbrush and a rubber pestle. Each subsample was manually passed through a 2 mm mesh sieve. Sieving was accomplished at ½-*phi* intervals between 16 mm and 250 μ. To prevent sieve overloading, the <2 mm fraction was passed through a Riffle Splitter and a sample of approximately 100 grams was obtained. (Folk, 1974). The fraction <250 μ was retained for further analysis. The truncation point of 250 μ was selected because particles finer than 250 μ are likely to travel in suspension (Sundberg, 1956).

3.4 Previous Bed Material Surveys

Bed material surveys were conducted on the Waipaoa River by the Poverty Bay Catchment Board, in 1950, 1956 and 1960. Particle size statistics obtained by these surveys were used to ascertain if the bed material particle size had changed appreciably during the last 50 years. The exact method used to obtain the bed material samples for the 1950, 1956 and 1960 surveys are unknown. For this reason, conclusions drawn from the comparison of these particle size data to the present survey must be considered tentative.

Additional bed material samples were obtained by the Gisborne District Council in 1988, 1993 and 1994. Samples were collected in 1988 from 6 sites along the river, corresponding to the sampling sites at 5, 11, 18, 24, 35 and 38 km in the present study, and from 4 sites in the lower reaches of the river in October 1993, corresponding to the sampling sites at 2, 7, 9, and 10 km. Separate samples of the surface and subsurface, plus 3 samples of the surface and subsurface combined, were obtained from across the exposed bar surface. Approximately ½ m^3 of material, that weighed approximately 30-40 kg, was removed for each sample (Peacock, personal communication 1996). Particle size statistics were determined for individual samples, as well as for the 5 samples combined.

Bed material samples also were obtained from the Waipaoa River by the Gisborne District Council in December 1994 from near Whatatutu, corresponding to the 74 km sampling site in the present study. Five samples were obtained from exposed bar surfaces across the river. The surface and subsurface were sampled separately. Particle size statistics were calculated for each individual sample, plus the 'total' sample, consisting of all subsurface samples combined (Peacock, personal communication 1996). These independently collected samples were used as a test of the representational accuracy of the samples obtained in this study. Approximately 400 kg of material was obtained in total (Peacock, personal communication 1996), and of this, a subsample of 6-10 kg from each of the 5 samples was analysed by sieving (Carlyle, personal communication 1997).

3.5 Statistical Analysis

All statistical tests and analysis were carried out using standard PC software (Novell, Inc. Quattro Pro, and Golden Software Grapher). Sample correlation coefficients (R^2) were calculated to test the strength of the relationships between the bed material particle size and various morphologic variables, such as local slope, reach slope, and drainage basin area. Sample correlation coefficients were calculated according to the method presented in Ott and Mendenhall (1990). The degree of correlation was assigned using the limits presented in Table 3.1. The significance of downstream trends were assessed using the coefficient of determination calculated by the Grapher programme. Mathematical fits describing the downstream variation in particle size and slope also were calculated by the Grapher programme. To determine if there was a significant difference between population fining coefficients, particle shapes, and slopes, the students t test was employed.

Table 3.1 Verbal limits and the corresponding correlation coefficients employed in this thesis.

Correlation coefficients	Verbal limits
>0.84	very strong
0.7 - 0.84	strong
0.49 - 0.69	moderate
0.4 - 0.49	weak
0.1 - 0.39	very weak
< 0.1	negligible

Particle size parameters such as the D_{50} , which is the particle diameter at which 50 % of the total sample is finer, and Trask's sorting coefficient were calculated using a programme developed by Stevens and Hubbell (1986). Other particle size parameters such as inclusive graphic standard deviation, skewness, etc, were calculated by formulae given by Folk (1974). Particle size modes, as well their corresponding proportion, standard deviation and skewness were calculated by a program developed by Wohletz (1996).

To obtain the particle size distribution for the entire bulk sample comprising all three particle size fractions (>16, 16-2 mm, and <2 mm) obtained by splitting the bulk sample, each fraction was multiplied by the splitting factor calculated by the method of Folk (1974). In this manner it was ensured that each particle size fraction represented the correct proportion of the total bulk sample weight.

The data obtained from grid-by-number sampling were tabulated into ½-*phi* particle size intervals, cumulative frequency distributions were drawn up, and the particle size parameters were manually read off the cumulative frequency graphs.

Particle size statistics for previous bed material surveys provided by the Gisborne District Council, were read directly from cumulative frequency plots that were provided with the survey reports.

Pebble shape parameters used in this thesis are Maximum Projection Sphericity (MPS), the Corey Shape Index (CSI), the Disk-Rod Index (DRI), and a flatness index (FI). The formulae employed to calculate these parameters are presented in Table 3.2. The ratios of short:long, short:intermediate, and intermediate:long also were investigated.

Table 3.2 Pebble shape parameters used in this thesis.

Parameter	Formulae	Author
MPS	$\sqrt[3]{\frac{S^2}{LI}}$	Sneed & Folk, 1958
CSI	$S/(I*L)^{½}$	Corey, 1949 (renamed by Illenberger, 1991)
DRI	(L-I)/(L-S)	Sneed & Folk, 1958 (named by Illenberger, 1991)
Flatness Index	(L+I)/S	Wentworth, 1922 (from Dobkins & Folk, 1970)

Pebble shape classifications were performed using an improvised Folk Form Triangle (Folk, 1974), as recommended by Illenberger (1991). Pebble shape was assessed for sandstone, siltstone and argillite pebbles, because these were the only lithologies that were consistently present in sufficient numbers to undertake statistically meaningful analyses.

3.6 Associated Data

***Local Bed Slope*:** Bed slope was measured because it has been proven in many studies that bed material size is highly correlated to bed slope (Hack, 1957; Penning-Rowsell & Townshend, 1978; Ferguson & Ashworth, 1991). Local bed slope was recorded at each site with a level and staff. Measurements were made over a 100 m distance, at points 50 m upstream and 50 m downstream of the sampling point. The staff was placed at the waters edge, or at the water surface level, recording the water surface slope.

Cross section data: The mean bed level at each cross-section measured by the Gisborne District Council was used to compute a longitudinal profile for the river. Average reach slope was calculated by the difference in mean bed level divided by the distance between successive cross sections. Reach slopes were averaged to correspond to the 1 km sampling intervals, because the cross sections were located at different sites. Channel width and depth were interpreted from the 1995/6 GDC cross section surveys. Channel width corresponds to the width of active bed composed of sand and gravel (shingle), and channel depth corresponds to bank full depth (Hosking, 1981).

The main objective of this thesis is to determine the processes responsible for producing downstream fining in the Waipaoa River. The results of the 1995/6 bed material survey are presented in three sections that pertain to; particle size, shape and lithology, respectively. The size, shape and lithological characteristics of a river's bed material, along the length of the river, are closely related to other morphological variables of the drainage basin. Depending upon the spatial and temporal scales employed, the bed material may appear to be an independent or a dependent variable (Schumm & Lichty, 1965). Various morphologic variables are listed for each sampling site in the Waipaoa River in Table 4.1.

Particle size; At any given point, the bed material size is determined by the lithology and size characteristics of the sediment supplied to the channel, and the distance downstream from the sediment input (Miller, 1958). The size of the bed material also is closely related to the sediment transporting capacity of the river (Lisle, 1995). Particle size statistics for the bed material samples obtained from the Waipaoa River are presented in Tables 4.2, 4.3, and 4.4. Particle size statistics for the bulk sieve analyses of the subsurface bed material samples are presented in Table 4.2. Particle size statistics for the grid-by-number samples are presented in Table 4.3. Particle size statistics obtained from the primary tributaries are presented in Table 4.4.

All particle size statistics are presented as percentiles, in which D_x represents the diameter (D in mm) at which x % of the sample is finer. For example, with a D_{50} of 2.67 mm, 50% of the particles within the sample are finer than 2.67 mm. Standard particle size measures characterising the particle size distributions are presented in Table 4.5.

Table 4.1 Drainage basin, river, and reach characterisitcs.

Site km	Drainage Area[2] (km²)	Reach Slope[1] (m/km)	Local Slope (m/km)	Cross-section[1] Width (m)	Depth (m)	Area (m²)
0	2181.49	-	-	419.9	3.2	1322.7
1	2181.47	-0.0003	0.0018	365.0	3.8	1383.2
2	2181.44	-0.0001	0.0008	274.7	4.1	1117.8
3	2181.41	0.0005	0.0012	180.0	4.5	809.1
4	2181.38	0.0003	-	171.0	4.5	769.3
5	1840.83	-0.0004	0.0003	155.2	5.1	790.0
6	1837.71	0.0003	0.0006	160.0	5.7	913.6
7	1835.86	0.0007	0.0003	139.6	5.3	740.6
8	1834.09	0.0003	0.0005	113.2	6.9	776.2
9	1832.37	0.0005	0.0005	84.7	7.7	648.0
10	1832.24	0.0005	0.0000	67.0	8.0	536.7
11	1831.45	0.0005	0.0004	67.4	8.9	598.8
12	1826.43	0.0004	0.0004	56.7	9.2	519.9
13	1826.38	0.0005	0.0001	45.8	9.3	426.4
14	1826.07	0.0009	0.0004	54.9	9.5	521.0
15	1813.59	0.0007	0.0001	54.3	10.0	541.4
16	1785.78	0.0005	0.0006	49.0	10.4	508.8
17	1781.38	0.0007	0.0003	54.0	9.9	533.8
18	1778.77	0.0005	0.0003	56.8	9.6	542.4
19	1731.02	0.0007	0.0004	59.1	9.5	559.1
20	1731.00	0.0006	0.0002	52.4	9.5	495.5
21	1730.98	0.0005	0.0007	55.4	9.8	544.3
22	1722.29	0.0008	0.0002	50.6	9.8	495.1
23	1722.29	0.0014	-	43.6	10.4	452.0
24	1722.28	0.0004	0.0001	42.1	10.0	421.3
25	1722.28	-0.0001	-	51.9	9.5	492.3
26	1722.27	0.0004	-	68.0	9.2	627.0
27	1722.26	0.0013	-	76.0	8.6	653.5
28	1722.24	0.0009	0.0012	64.7	8.3	535.7
29	1721.88	0.0008	0.0001	70.5	7.9	560.1
30	1719.50	0.0005	0.0008	78.2	7.5	583.0
31	1710.91	0.0004	0.0003	61.9	6.8	422.1
32	1710.91	0.0004	0.0002	59.9	6.6	397.7
33	1710.25	0.0009	0.0003	88.3	7.1	626.1
34	1702.31	0.0009	0.0007	85.2	8.6	729.7
35	1690.51	0.0008	0.0010	83.6	8.6	719.8
36	1686.63	0.0011	0.0002	160.1	7.3	1162.3
37	1686.41	0.0004	0.0001	82.7	5.8	483.1
38	1686.34	0.0011	0.0004	82.0	5.3	433.0
39	1582.57	0.0009	0.0002	88.3	6.5	571.0
40	1582.45	0.0008	0.0013	90.7	6.5	589.6
41	1581.00	0.0011	-	80.5	6.0	482.2
42	1580.00	0.0016	-	203.9	6.5	1334.2
43	1579.90	0.0011	0.0001	119.2	7.4	884.5
44	1579.61	0.0008	-	98.3	9.4	924.0
45	1577.13	0.0017	0.0006	109.8	7.6	831.4
46	1574.71	0.0012	0.0003	106.4	6.3	671.4
47	1573.73	0.0016	0.0010	92.7	6.2	574.4
48	1572.61	0.0010	0.0002	73.5	-	-
49	1569.28	0.0013	0.0008	97.8	6.4	625.6
50	1435.08	0.0019	0.0010	105.4	7.2	761.0
51	1434.25	0.0018	0.0011	143.0	5.8	822.0

(-) data not available

[1] Data source: Gisborne District Council

[2] Calculated from DEM

Table 4.1 Drainage basin, river, and reach characterisitcs (continued).

Site	Drainage Area [2]	Reach Slope[1]	Local Slope	Cross-section[1]		
				Width	Depth	Area
km	(km²)			(m)	(m)	(m²)
52	1433.68	0.0008	0.0005	105.7	5.8	607.5
53	1422.84	0.0017	0.0008	93.3	4.4	410.5
54	1422.16	0.0019	0.0014	110.2	4.5	497.2
55	771.69	0.0017	-	143.9	4.6	664.7
56	769.71	0.0013	0.0006	131.0	5.3	689.0
57	722.89	0.0016	0.0014	108.8	5.6	606.9
58	717.98	0.0015	0.0009	104.2	5.7	590.8
59	711.96	0.0019	0.0002	103.5	5.2	537.2
60	711.94	0.0022	-	96.7	4.0	389.8
61	711.94	0.0019	0.0008	116.8	3.4	391.3
62	711.93	0.0023	0.0011	91.4	3.9	355.2
63	711.92	0.0025	0.0008	85.6	4.4	378.4
64	711.91	0.0021	0.0011	115.1	3.3	381.0
65	709.24	0.0015	0.0012	79.5	4.4	349.9
66	709.24	0.0015	0.0015	98.3	6.6	649.0
67	709.24	0.0020	0.0007	77.3	6.6	509.9
68	694.55	0.0028	0.0012	140.5	-	-
69	691.63	0.0038	0.0010	625.0	3.5	2181.3
70	691.50	0.0045	0.0012	171.0	2.9	495.9
71	691.35	0.0037	0.0015	382.4	2.7	1044.0
72	493.99	0.0032	0.0017	236.9	2.7	630.0
73	479.96	0.0032	0.0017	125.4	3.4	419.9
74	478.70	0.0034	0.0027	159.4	4.1	655.1
75	461.51	0.0036	0.0018	103.4	3.6	368.4
76	238.46	0.0036	0.0025	47.3	3.0	142.8
77	233.49	0.0038	0.0038	45.2	3.9	174.1
78	233.37	0.0041	0.0025	35.4	4.7	166.0
79	231.37	0.0042	0.0027	27.7	4.7	130.2
80	230.46	0.0046	0.0021	42.4	4.3	183.8
81	222.07	0.0046	0.0017	57.0	4.0	226.9
82	220.81	0.0049	0.0022	52.0	3.5	181.6
83	219.24	0.0053	0.0027	52.6	2.4	126.1
84	218.18	0.0056	0.0026	65.0	2.9	187.8
85	209.69	0.0062	0.0027	74.0	2.8	209.4
86	188.70	0.0055	0.0023	89.8	3.9	347.5
87	188.68	0.0055	-	77.1	3.3	254.3
88	188.16	0.0062	-	37.0	2.7	101.0
89	186.40	0.0076	-	48.0	1.1	54.7
90	184.89	0.0081	-	40.0	-	-
91	184.12	0.0081	-	41.4	6.8	281.1
92	182.14	0.0090	0.0044	66.2	2.2	147.0
93	135.46	0.0090	0.0056	324.6	1.8	587.5
94	132.75	0.0106	0.0031	321.0	1.4	449.4
95	101.48	-	-	347.8	-	-
96	92.57	0.0107	0.0072	378.4	-	-
97	91.98	0.0107	0.0050	390.0	1.8	713.7
98	75.07	0.0114	0.0052	378.3	-	-
99	73.53	0.0121	0.0066	203.7	1.7	342.2
100	72.41	-	0.0053	107.7	-	-
101	52.86	-	0.0052	136.7	-	-
102	51.83	-	0.0071	126.5	-	-

(-) data not available

[1] Data source: Gisborne District Council

[2] Calculated from DEM

Table 4.2 Bulk sieve analysis - Waipaoa River.

km	D_5	D_{16}	D_{25}	D_{35}	D_{50}	D_{65}	D_{75}	D_{84}	D_{90}	D_{95}	%sand
0	0.15	0.18	0.19	0.21	0.23	0.26	0.28	0.03	0.33	0.36	100
1	0.01	0.15	0.23	0.26	0.27	0.29	0.32	0.34	0.37	0.45	100
2	0.04	0.06	0.08	0.10	0.13	0.17	0.21	0.27	0.33	0.44	100
3	0.10	0.23	0.24	0.27	0.31	0.33	0.35	0.38	0.40	0.41	100
4	0.18	0.22	0.23	0.25	0.28	0.31	0.33	0.36	0.40	0.46	100
5	0.14	0.18	0.20	0.22	0.26	0.31	0.34	0.41	0.49	0.66	100
6	0.14	0.24	0.31	0.39	0.50	0.65	0.80	1.25	1.74	3.42	93
7	0.15	0.25	0.32	0.40	0.51	0.68	0.85	1.10	1.33	1.58	99
8	0.08	0.39	0.53	0.65	0.85	1.10	1.35	1.74	2.24	3.20	84
9	0.25	0.48	0.67	0.90	1.30	1.99	2.90	5.05	8.06	11.71	65
10	0.22	0.43	0.58	0.74	1.05	1.40	1.73	2.74	6.56	16.52	81
11	0.34	0.60	0.81	1.10	1.64	2.67	4.23	7.66	11.28	17.10	58
12	0.17	0.56	0.69	0.84	1.13	1.58	2.19	3.46	6.24	11.53	71
13	0.54	1.04	1.42	1.99	3.20	5.69	8.27	11.82	15.05	22.93	35
14	0.27	0.49	0.73	1.22	2.21	3.74	6.00	9.39	13.49	18.18	47
15	0.30	0.51	0.70	1.29	3.02	6.52	10.83	16.42	20.02	24.31	42
16	0.39	0.65	0.94	1.49	3.43	7.89	12.10	18.06	23.12	29.63	40
17	0.36	0.56	0.69	0.86	1.16	1.63	2.26	3.58	5.94	11.13	72
18	0.37	0.60	0.74	0.96	1.68	3.27	5.50	9.07	16.07	19.84	53
19	0.41	0.90	1.39	1.86	2.60	3.53	4.58	6.29	8.02	11.28	37
20	0.30	0.58	0.79	1.26	2.65	6.05	9.82	14.56	18.71	24.37	44
21	0.16	0.43	0.70	0.95	1.34	1.91	2.63	4.27	7.72	14.24	66
22	0.65	1.00	1.33	1.81	2.80	4.66	7.38	11.56	15.65	21.97	38
23	0.36	0.62	0.76	0.95	1.41	2.59	4.47	8.94	13.71	20.96	58
24	0.59	1.21	1.68	2.26	3.44	5.62	8.01	12.74	18.06	23.56	30
25	0.07	0.79	1.27	2.27	7.22	15.64	21.82	28.54	34.51	42.15	28
26	0.37	0.67	0.96	1.33	2.13	3.53	5.74	9.20	12.66	17.39	48
27	0.27	0.59	0.89	1.57	3.59	7.12	9.98	12.99	15.65	17.94	39
28	0.25	0.73	1.11	1.78	3.85	8.09	10.24	14.68	18.70	23.75	36
29	0.49	0.64	0.74	0.88	1.12	1.54	2.22	3.98	7.64	16.30	73
30	0.38	0.80	1.11	1.61	3.25	7.11	11.71	18.11	24.37	33.21	37
31	0.40	1.00	1.36	1.80	2.63	3.90	5.66	7.94	10.56	16.16	39
32	0.28	0.61	1.07	1.85	3.07	5.11	7.24	10.17	12.81	16.64	37
33	0.27	0.44	1.18	1.66	2.45	3.68	5.50	8.11	10.93	17.47	42
34	0.27	0.48	0.73	1.64	7.63	14.86	20.14	25.31	29.56	34.52	36
35	0.50	1.10	1.64	2.53	5.36	9.71	15.20	22.16	29.04	36.69	30
36	0.23	1.06	1.45	1.87	2.60	3.80	6.06	10.87	19.50	35.05	35
37	0.69	1.24	1.63	2.18	3.47	6.35	9.76	16.28	19.26	24.12	31
38	0.51	1.12	1.80	2.87	5.46	9.15	12.51	16.68	20.02	24.68	26
39	0.25	0.69	1.09	1.78	3.53	6.43	9.08	12.89	17.20	23.72	36
40	0.83	1.71	2.27	2.92	4.26	6.46	8.52	11.49	14.57	20.01	18
41	0.44	0.82	1.66	2.74	5.71	9.27	12.51	16.87	22.45	28.58	28
42	0.43	0.58	0.67	0.82	1.29	2.02	3.56	7.72	13.45	22.86	65
43	0.08	0.91	1.30	1.89	2.91	4.29	5.82	7.60	9.33	13.25	32
44	0.67	1.70	2.40	3.27	5.17	8.04	11.02	17.27	21.84	27.64	19
45	0.41	0.91	1.32	1.85	2.93	5.24	7.91	12.11	17.42	23.95	37
46	0.27	0.52	0.86	1.88	4.07	7.46	10.73	15.69	20.62	26.99	36
47	0.68	1.21	1.71	2.45	3.95	6.25	8.18	10.57	12.91	16.58	28
48	0.39	0.65	0.96	1.60	3.63	8.81	12.26	17.70	24.00	32.41	39
49	0.51	1.07	1.85	2.89	4.79	7.26	9.33	12.07	14.77	19.31	26
50	0.46	0.91	1.53	2.58	4.98	8.62	11.93	16.99	21.31	28.44	30
51	0.25	1.24	2.35	4.61	11.05	21.48	29.32	39.43	48.88	61.45	20

Table 4.2 Bulk Sieve analysis - Waipaoa River (continued)

km	D_5	D_{16}	D_{25}	D_{35}	D_{50}	D_{65}	D_{75}	D_{84}	D_{90}	D_{95}	%sand
52	0.39	0.66	0.94	1.43	3.00	5.81	8.29	11.47	15.53	24.48	42
53	0.33	0.60	0.94	1.92	4.49	8.01	12.07	17.84	22.93	30.37	35
54	0.25	0.36	0.44	0.59	1.53	4.87	10.95	20.44	26.20	34.74	53
55	0.47	1.00	1.72	2.89	5.19	8.08	10.03	12.62	15.21	19.17	28
56	0.36	0.72	1.20	1.95	3.67	6.86	10.51	16.93	23.62	32.70	36
57	0.47	1.01	1.61	2.65	5.18	8.77	12.93	19.77	25.94	35.65	28
58	0.35	0.70	0.97	1.31	2.18	3.76	6.30	11.72	20.09	31.20	48
59	0.30	0.56	0.83	1.46	3.24	6.21	9.49	17.34	22.31	28.56	40
60	0.46	0.93	1.55	2.70	5.68	9.43	18.11	24.11	29.50	34.32	29
61	0.46	0.93	1.49	2.40	4.31	7.59	10.86	16.24	20.43	26.37	31
62	0.57	0.89	1.15	1.49	2.22	3.33	4.63	7.03	10.41	18.19	46
63	0.35	0.63	0.90	1.34	2.71	5.75	8.65	12.54	17.43	25.45	44
64	0.35	0.68	1.13	2.02	4.86	9.12	12.72	16.87	20.50	24.71	35
65	0.35	0.69	1.16	2.07	3.75	7.41	11.95	19.41	25.13	33.14	34
66	0.47	1.01	1.57	2.52	4.96	8.59	12.15	17.45	22.68	28.51	30
67	0.48	1.10	1.75	2.89	5.62	8.84	11.89	16.30	22.77	28.55	27
68	0.31	0.80	1.27	1.85	2.99	4.72	6.71	9.99	16.80	22.82	37
69	0.32	0.61	0.94	1.52	3.18	6.74	10.65	16.23	21.42	29.10	41
70	0.34	0.55	0.68	0.91	1.59	4.35	8.99	15.98	24.77	34.86	54
71	0.38	0.95	1.40	2.10	3.77	8.10	15.90	25.22	34.02	48.57	33
72	0.33	0.63	1.15	2.21	4.44	7.67	10.97	17.11	22.92	31.66	33
73	0.44	0.70	0.93	1.24	1.98	3.59	6.71	16.98	24.41	35.36	50
74	0.22	0.60	0.99	1.73	3.71	7.28	10.71	16.80	24.19	35.22	37
75	0.50	1.14	1.80	2.70	4.48	7.47	11.58	18.54	23.23	32.49	26
76	0.26	0.46	0.79	1.50	3.50	7.52	11.67	18.10	23.91	33.11	40
77	0.45	1.01	1.58	2.60	5.74	10.49	15.03	25.98	45.03	90.95	29
78	0.24	0.52	0.70	1.09	2.42	7.00	10.26	16.96	23.86	41.27	46
79	0.24	0.60	1.06	1.95	3.90	7.10	9.71	14.18	18.16	22.95	35
80	0.40	0.87	1.36	2.13	3.95	8.23	12.44	17.95	23.98	33.44	33
81	0.31	0.55	0.73	1.12	2.31	5.26	8.32	13.01	18.78	28.01	47
82	0.28	0.49	0.65	1.00	2.35	5.82	9.87	18.92	26.42	37.67	48
81	0.31	0.55	0.73	1.12	2.31	5.26	8.32	13.01	18.78	28.01	47
82	0.28	0.49	0.65	1.00	2.35	5.82	9.87	18.92	26.42	37.67	48
83	0.20	0.57	0.90	1.54	3.61	7.93	12.50	19.04	24.48	32.31	38
84	0.22	1.15	2.07	3.40	6.50	10.22	13.53	17.93	22.29	27.81	21
85	0.24	0.70	1.26	2.33	5.85	11.03	16.38	23.29	30.24	43.17	32
86	0.36	0.72	1.24	2.31	5.03	90.38	14.59	20.89	26.95	34.66	33
87	0.23	0.60	0.97	1.62	3.64	8.63	13.58	19.25	25.10	34.18	38
88	0.27	1.74	3.19	5.00	8.13	11.98	15.45	20.31	26.52	36.72	16
89	0.21	0.68	1.08	1.89	5.32	15.88	23.73	33.49	45.64	60.27	34
90	0.36	0..811	1.24	1.97	4.55	11.88	18.86	27.99	36.26	45.66	34
91	0.33	0.61	0.84	1.21	2.37	5.79	9.44	15.40	22.38	31.82	47
92	0.26	0.58	0.94	1.54	3.16	6.81	11.28	18.86	27.93	43.43	41
93	0.25	0.61	1.05	1.62	3.57	8.00	16.00	23.75	32.01	39.48	39
94	0.24	0.62	1.06	1.65	3.03	6.03	11.42	19.95	26.84	35.21	39
95	0.42	0.89	1.34	1.98	3.87	8.99	15.43	23.57	31.76	38.55	34
96	0.18	0.65	1.59	3.23	7.62	13.72	20.22	29.72	45.29	63.24	27
97	0.29	1.02	1.85	3.04	5.72	10.60	28.96	30.98	37.02	54.06	25
98	0.04	0.60	1.33	2.41	5.07	11.56	20.07	27.96	34.93	44.42	25
99	0.18	0.72	1.55	3.23	8.47	19.25	30.22	43.23	55.56	66.79	26
100	0.06	0.38	0.99	2.07	4.32	8.47	17.56	31.05	50.21	66.16	29
101	0.03	0.92	2.15	3.49	6.38	11.25	17.01	24.59	32.62	47.03	18
102	0.11	0.59	1.09	2.02	5.20	11.13	18.00	28.67	40.79	56.20	32

Table 4.3 Particle size statistics obtained by grid-by-number, and Wolman sampling.

km	D_5	D_{16}	D_{25}	D_{35}	D_{50}	D_{65}	D_{75}	D_{84}	D_{90}	D_{95}
5	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8
6	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	3.4	4.6
7	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	<2.8	4.8	6.3	7.2
8	<2.8	<2.8	<2.8	<2.8	<2.8	3.5	5.0	6.4	7.7	9.4
9	<2.8	<2.8	3.4	4.3	5.5	7.2	8.6	10.2	11.3	13.7
11	3.6	4.9	5.5	6.4	7.8	10.1	12.3	14.7	17.0	20.1
12	<2.8	4.0	5.6	7.1	9.9	13.2	15.7	19.0	21.5	25.9
14	3.7	4.7	5.3	6.0	7.2	8.4	9.6	10.8	12.1	14.9
15	3.3	4.9	5.9	7.3	9.0	10.6	12.0	14.1	15.5	19.4
16	4.3	6.7	8.7	10.4	13.1	15.8	19.5	23.4	27.0	30.1
20	3.9	4.7	5.2	6.0	7.3	8.9	10.0	11.1	13.7	17.5
22	4.3	7.1	9.9	12.3	15.6	18.9	21.0	23.3	27.7	30.1
24	4.1	5.2	6.3	7.5	9.6	12.0	14.1	16.3	19.5	22.0
28	3.0	3.8	4.9	6.5	9.5	13.0	15.1	18.5	21.2	25.8
30	4.1	5.2	6.8	9.0	12.9	17.9	20.7	24.0	27.7	30.8
31	5.0	6.6	7.7	8.7	10.3	12.1	14.9	17.8	20.0	22.0
33	4.3	6.0	7.6	8.9	10.8	13.8	16.6	20.5	23.5	28.0
34	5.3	6.8	8.0	9.2	11.3	14.9	17.6	20.5	22.3	27.0
37	6.0	8.1	10.1	12.3	15.8	20.2	24.3	30.9	36.1	41.0
39	5.0	8.0	9.5	10.8	13.0	15.5	18.6	22.5	28.8	38.1
43	6.0	7.7	9.0	10.9	13.0	15.7	18.4	21.0	23.4	28.7
47	6.0	8.5	10.1	12.0	15.2	18.4	20.6	22.5	26.6	30.1
48	3.3	6.0	7.9	9.8	13.4	17.8	21.0	25.0	28.9	31.8
52	5.5	7.8	10.1	13.2	17.9	22.0	27.2	33.0	38.0	42.0
55	3.9	5.9	7.1	8.4	10.3	12.6	14.5	16.4	18.8	21.0
62	3.7	8.0	10.2	12.5	15.7	19.1	21.5	26.0	31.1	37.9
66	5.5	8.3	9.5	10.9	15.1	20.0	23.7	30.0	35.9	41.5
75	4.4	6.1	9.1	11.0	15.1	19.1	22.0	29.1	36.0	42.3
94	10.5	14.1	17.0	20.8	26.8	33.1	38.5	43.7	51.0	60.0
95	20.8	28.0	33.0	36.5	41.8	49.0	56.6	63.2	75.5	88.0
96	13.8	18.7	21.5	25.0	30.1	41.1	51.0	60.0	70.0	87.0
97	12.0	19.5	23.1	27.1	34.0	44.1	53.8	62.0	77.0	108.0
98	12.1	20.0	24.8	29.0	35.3	42.0	49.0	65.0	73.5	85.2
99	8.2	10.9	12.9	15.0	18.8	22.5	27.5	32.0	37.5	42.5
100	9.0	12.4	14.0	15.8	19.7	24.2	28.2	32.0	40.0	53.0
101	12.7	20.0	23.8	36.2	29.9	34.7	39.2	43.0	49.5	59.9
102	12.7	19.1	23.1	26.7	32.0	41.0	47.9	55.0	60.0	60.4
103	10.6	16.7	18.9	22.0	26.1	30.3	35.0	42.0	50.4	64.0
104	11.5	18.0	23.0	27.0	33.2	41.0	47.1	58.0	66.9	87.0

Table 4.4 Particle size statistics of tributaries in the Waipaoa River.

Tributary	D_5	D_{16}	D_{25}	D_{35}	D_{50}	D_{65}	D_{75}	D_{84}	D_{90}	D_{95}	%sand	sorting
Waihora	0.1	0.3	0.7	3.0	8.2	13.8	19.2	24.9	29.4	33.5	28	5.15
Waikohu	0.2	0.7	1.9	4.2	9.4	17.7	23.8	30.4	35.5	42.2	24	3.50
Waingaromia	0.0	1.1	2.9	5.4	9.7	16.4	21.2	26.9	32.7	43.7	14	2.69
Mangatu 1	0.3	0.5	0.7	1.1	2.2	4.5	7.9	14.3	20.5	27.1	48	3.31
Mangatu 2	0.3	0.5	0.9	1.7	4.4	10.5	16.0	21.8	26.7	34.9	38	4.17
Mangaorongo	0.2	1.0	7.7	19.9	36.9	52.4	64.0	67.1	69.9	73.7	16	2.88
Te Weraroa	0.2	0.5	1.0	1.6	3.2	6.2	9.6	17.4	23.6	32.8	38	3.15
Matau	0.2	0.6	0.8	1.2	2.1	3.6	5.7	10.2	19.2	37.8	47	2.63
Matakonekone	0.3	0.6	0.9	1.4	2.8	5.5	8.5	14.2	20.8	32.7	42	3.03
Tikihore	0.5	1.7	2.7	4.0	6.9	11.1	15.1	21.1	26.3	33.6	18	2.35

Table 4.5 Characteristic parameters describing the particle size distributions.

km	D_{50} (mm)	D_{90} (mm)	Mean (mm)	Sorting (mm)	Skewness (Ø)	Std Dev (Ø)	Kurtosis (Ø)
0	0.23	0.33	0.23	1.50	0.004	0.387	1.01
1	0.20	0.30	0.16	1.50	-0.135	0.884	0.79
2	0.13	0.33	0.13	1.65	-0.001	1.072	1.00
3	0.30	0.40	0.13	1.50	0.012	1.148	1.02
4	0.28	0.40	0.28	1.50	0.065	0.384	1.08
5	0.26	0.49	0.27	1.31	0.112	0.652	1.20
6	0.50	1.74	0.53	1.60	0.173	1.285	1.37
7	0.51	1.33	0.52	1.63	-0.013	1.056	1.00
8	0.85	2.24	0.83	1.58	-0.065	1.172	1.38
9	1.30	8.06	1.47	2.08	0.147	1.689	1.08
10	1.05	6.56	1.10	1.73	0.177	1.642	1.61
11	1.64	11.28	1.96	2.29	0.205	1.776	0.98
12	1.13	6.24	1.29	1.78	0.167	1.578	1.49
13	3.20	15.05	3.40	2.41	0.065	1.695	0.87
14	2.21	13.49	2.17	2.87	-0.012	1.989	0.82
15	3.02	20.02	2.94	3.92	-0.036	2.211	0.66
16	3.43	23.12	3.44	3.59	-0.003	2.145	0.70
17	1.16	5.94	1.32	1.80	0.262	1.424	1.20
18	1.68	16.07	2.09	2.73	0.241	1.849	0.81
19	2.60	8.02	2.45	1.82	-0.101	1.425	1.13
20	2.65	18.71	2.82	3.53	0.033	2.125	0.72
21	1.34	7.72	1.35	1.94	0.032	1.808	1.39
22	2.80	15.65	3.46	2.35	-0.009	1.655	0.84
23	1.41	13.71	1.98	2.42	0.354	1.856	0.94
24	3.44	18.06	3.72	2.19	0.072	1.666	0.97
25	7.22	34.51	5.46	4.15	-0.344	2.709	0.93
26	2.13	12.66	2.79	2.44	-0.219	1.787	0.81
27	3.59	15.65	3.03	3.36	-0.198	2.027	0.71
28	3.85	18.70	3.45	3.04	-0.155	2.080	0.84
29	1.12	7.64	1.42	1.73	0.460	1.422	1.30
30	3.25	24.37	3.61	3.25	0.071	2.103	0.78
31	2.63	10.56	2.75	2.02	0.023	1.555	1.06
32	3.07	12.81	2.67	2.43	-0.159	1.906	0.88
33	2.45	10.93	2.05	2.16	-0.121	1.967	1.11
34	7.63	29.56	4.53	5.24	-0.386	2.488	0.60
35	5.36	29.04	5.07	3.05	-0.079	2.021	0.79
36	2.60	19.50	3.11	2.04	0.132	1.936	1.44
37	3.47	19.26	4.13	2.44	0.147	1.704	0.81
38	5.46	20.02	4.67	2.64	-0.198	1.822	0.82
39	3.53	17.20	3.16	2.89	-0.140	2.053	0.88
40	4.26	14.57	4.37	1.94	0.006	1.383	0.99
41	5.71	22.45	4.29	2.75	-0.256	2.004	0.85
42	1.29	13.45	1.76	2.30	0.457	1.800	0.98
43	2.91	9.33	2.72	2.11	-0.249	1.876	1.39
44	5.17	21.84	5.33	2.14	-0.030	1.651	1.00
45	2.93	17.42	3.18	2.45	0.063	1.825	0.93
46	4.07	20.62	3.22	3.53	-0.190	2.228	0.74
47	3.95	12.91	3.70	2.19	-0.097	1.479	0.50
48	3.63	24.00	3.46	3.58	-0.027	2.162	0.71
49	4.79	14.77	3.95	2.24	-0.236	1.669	0.92
50	4.98	21.31	4.37	2.79	-0.145	1.925	0.82
51	11.05	48.88	8.15	3.53	-0.322	2.454	0.90

Table 4.5 Characteristic parameters describing the particle size distributions (continued).

km	D_{50} (mm)	D_{90} (mm)	Mean (mm)	Sorting (mm)	Skewness (Ø)	Std Dev (Ø)	Kurtosis (Ø)
52	3.00	15.53	2.83	2.97	-0.023	1.935	0.78
53	4.49	22.93	3.63	3.59	-0.172	2.217	0.73
54	1.53	26.20	2.24	4.97	0.275	2.536	0.63
55	5.19	15.21	4.03	2.42	-0.298	1.728	0.86
56	3.67	23.62	3.55	2.96	-0.030	2.123	0.72
57	5.18	25.94	4.70	2.84	-0.103	2.016	0.85
58	2.18	20.09	2.62	2.55	0.188	2.000	0.98
59	3.24	22.31	3.15	3.38	-0.034	2.237	0.77
60	5.68	29.50	5.04	3.42	-0.138	2.114	0.72
61	4.31	20.43	4.02	2.70	-0.088	1.916	0.84
62	2.22	10.41	2.41	2.00	0.166	1.501	1.02
63	2.71	17.43	2.78	3.09	0.034	2.017	0.78
64	4.86	20.50	3.82	3.36	-0.231	2.090	0.72
65	3.75	25.13	3.68	3.21	-0.027	2.198	0.80
66	4.96	22.68	4.44	2.78	-0.132	1.924	0.82
67	5.62	22.77	4.66	2.60	-0.207	1.866	0.88
68	2.99	16.80	2.88	2.30	-0.048	1.848	1.06
69	3.18	21.42	3.16	3.37	-0.010	2.166	0.76
70	1.59	24.77	2.40	3.63	0.350	2.232	0.74
71	3.77	34.02	4.49	3.37	0.106	2.246	0.82
72	4.44	22.92	3.64	3.09	-0.160	2.186	0.83
73	1.98	24.41	2.87	2.68	0.332	2.107	0.91
74	3.71	24.19	3.35	3.30	-0.101	2.305	0.87
75	4.48	23.23	4.56	2.54	-0.016	1.917	0.92
76	3.50	23.91	3.08	3.84	-0.091	2.388	0.74
77	5.74	45.03	5.33	3.08	-0.015	2.332	0.97
78	2.42	23.86	2.77	3.84	0.110	2.380	0.78
79	3.90	18.16	3.21	3.02	-0.202	2.136	0.84
80	3.95	23.98	3.95	3.02	-0.018	2.061	0.82
81	2.31	18.78	2.55	3.37	0.101	2.124	0.76
82	2.35	26.42	2.79	3.86	0.137	2.390	0.75
83	3.61	24.48	3.39	3.73	-0.099	2.386	0.80
84	6.50	22.29	5.11	2.55	-0.331	2.051	1.06
85	5.85	30.24	4.57	3.65	-0.220	2.397	0.82
86	5.03	26.95	4.23	3.43	-0.156	2.216	0.76
87	3.64	25.10	3.48	3.75	-0.070	2.340	0.77
88	8.13	26.52	6.59	2.20	-0.321	1.962	1.28
89	5.32	45.64	4.94	4.69	-0.101	2.647	0.75
90	4.55	36.26	4.69	3.90	-0.011	2.338	0.73
91	2.37	22.38	2.82	3.35	0.150	2.160	0.77
92	3.16	27.93	3.25	3.47	0.024	2.378	0.85
93	3.57	32.01	3.73	3.91	-0.006	2.426	0.76
94	3.03	26.84	3.35	3.29	0.034	2.345	0.86
95	3.87	31.76	4.33	3.40	0.060	2.170	0.76
96	7.62	45.29	5.29	3.57	-0.281	2.653	0.94
97	5.72	37.02	5.65	3.95	-0.076	2.374	0.78
98	5.07	34.93	4.40	3.88	-0.242	2.900	1.05
99	8.47	55.56	6.41	4.41	-0.252	2.781	0.82
100	4.32	50.21	3.69	4.20	-0.168	3.139	1.01
101	6.38	32.62	5.25	2.81	-0.321	2.813	1.48
102	5.20	40.79	4.45	4.07	-0.177	2.757	0.91

Particle size statistics for the bed material samples obtained by the Gisborne District Council in 1950, 1956 and 1960 are presented in Table 4.6. Particle size distributions for samples obtained by the Gisborne District Council in 1988, 1993, and 1994 are compared graphically to the particle size distributions obtained in the present study in Figures 4.1 - 4.3.

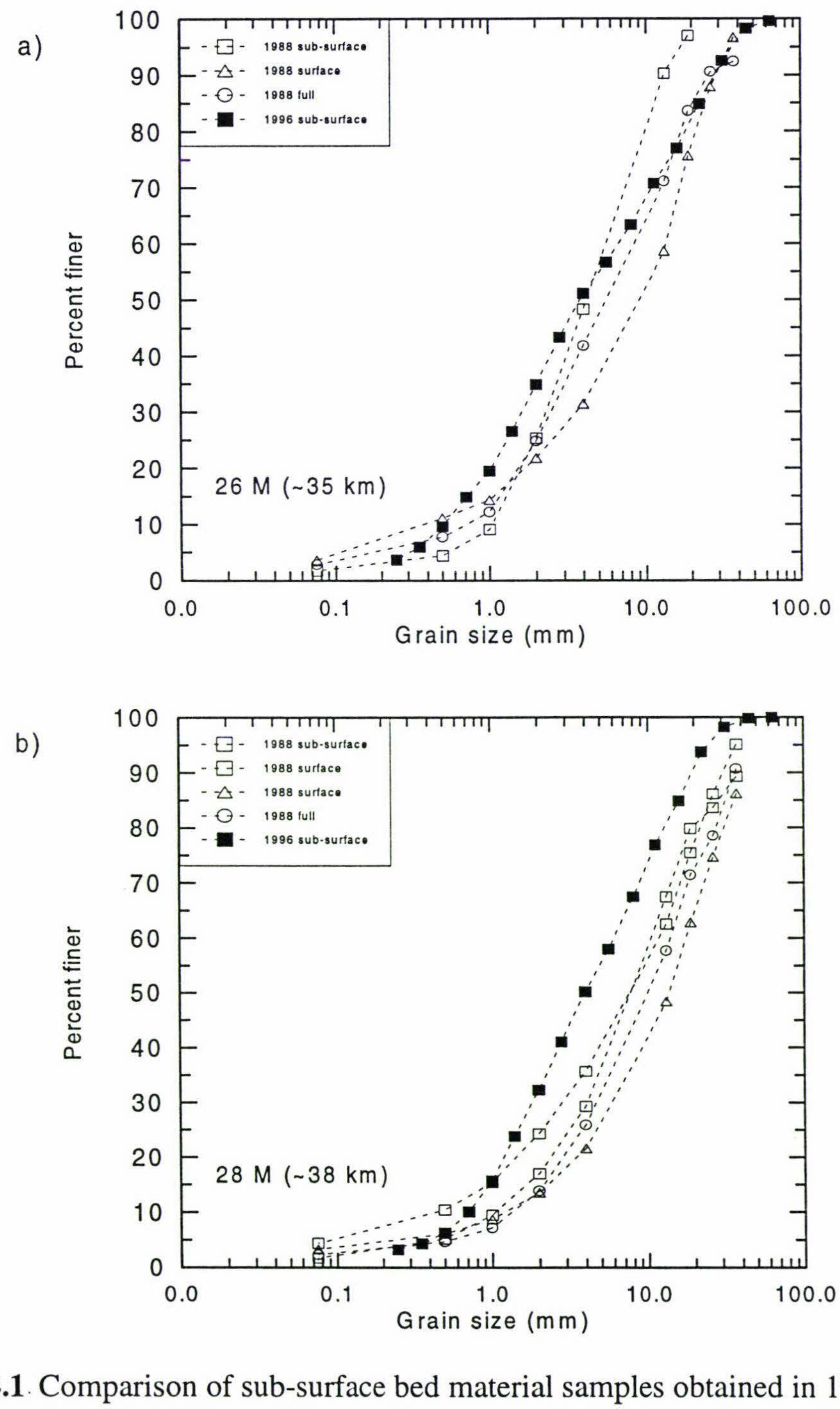


Figure 4.1 Comparison of sub-surface bed material samples obtained in 1988 and 1996, from the Waipaoa River at the upper end of the Flood Control Scheme, (a) at the 25M cross section, and (b) at the 28 M cross section, near Kaitaratahi. (Source of 1988 samples; GDC).

In 1993, bed material samples were obtained from the lower reaches of the Waipaoa River, corresponding to the 2 km, 7 km, 9 km, and 10 km sampling sites of the present survey, by the GDC. Up to four individual samples were obtained at each sampling site, and the particle size statistics for each sample, as well as for the combined 'total' sample were available for comparison to the present survey data. The particle size distributions obtained in 1993, and the corresponding particle size distributions obtained in 1995/6 graphically are compared in Figure 4.2.

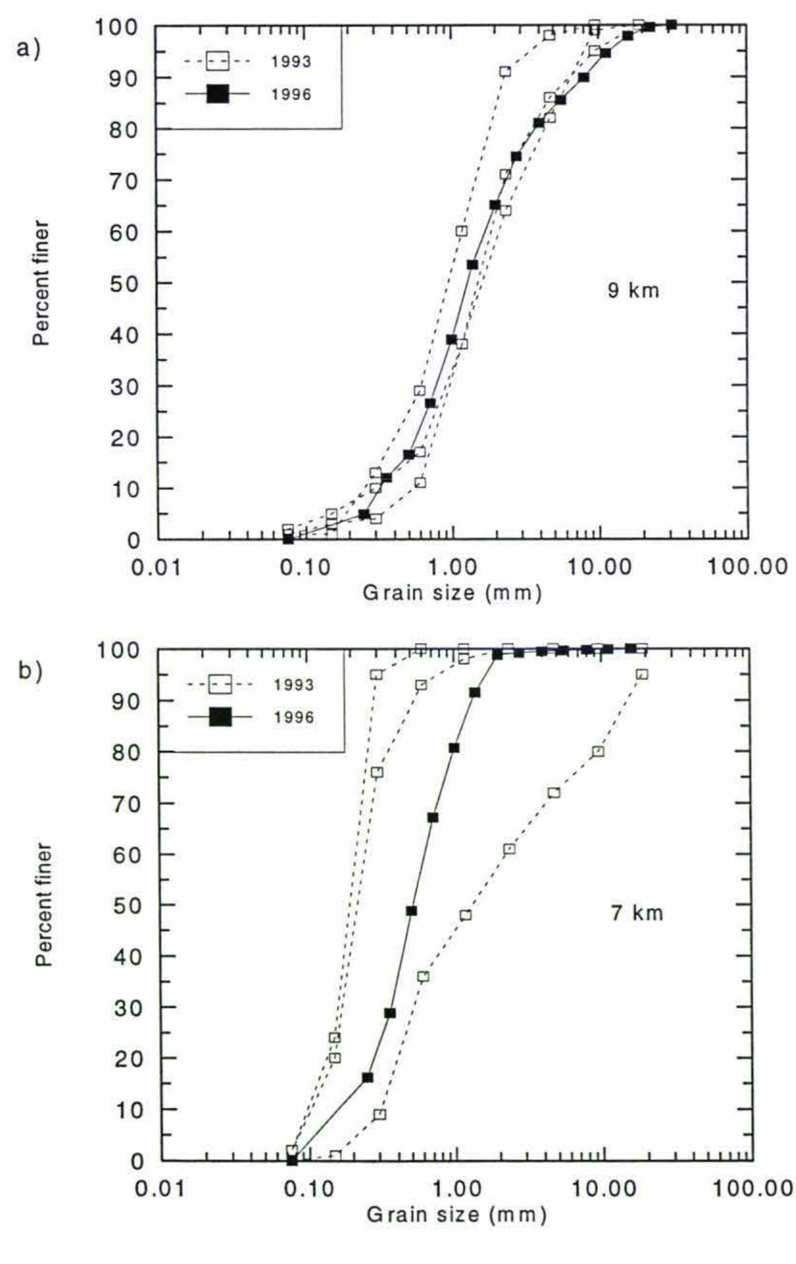


Figure 4.2 Comparison of bed material samples obtained from the lower reaches of the Waipaoa River in 1993 and 1996, at the sampling sites corresponding to the a) 9 km site, and b) the 7 km site in the present study, near Matawhero. (Source of 1993 samples; GDC).

In 1994, a single large composite sample was obtained from the subsurface bed material of the Waipaoa River, near Whatatutu, by the GDC. The composite was made up of 3 samples of the subsurface material, plus 2 samples of the combined surface and subsurface bed material. Cumulative particle size distribution curves of the 1994 and 1995/6 bed material samples are presented in Figure 4.3.

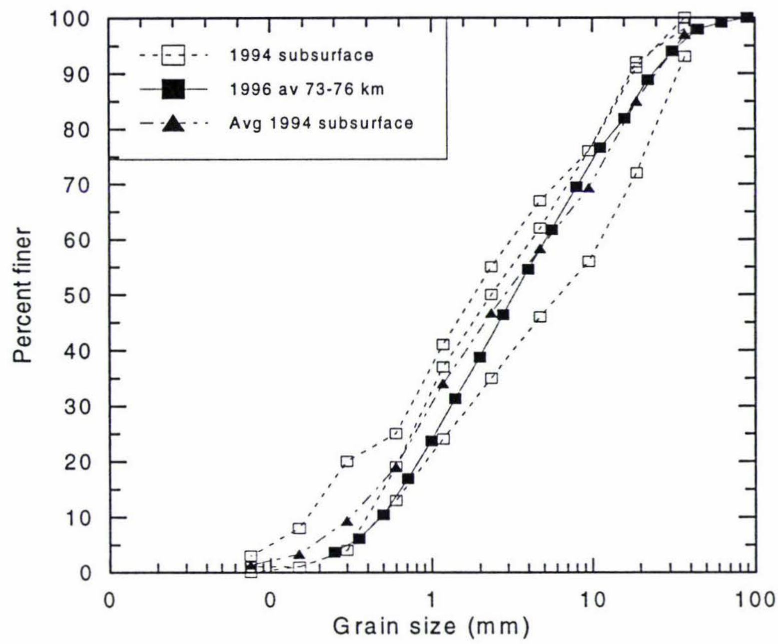


Figure 4.3 Comparison of bed material samples obtained from the middle reaches of the Waipaoa River in 1994 and 1996, at the sampling sites corresponding to the 74 km site in the present study, near Whatatutu (Source of 1994 samples; GDC).

The site that the bed material was taken from in 1994 corresponds approximately to the 74 km sampling site of the present survey, but the particle size data were compared to the average of the particle size data obtained from a 3 km reach, spanning from 73 km to 76 km. Very similar particle size distribution curves were obtained from both sets of data, and the D50 and D90 particle size statistics of the average of the sub-surface samples is within 0.5 mm from the 1996 statistics. These bed material samples were obtained by a slightly different method to the 1995/6 samples. Because they were obtained from exposed bars from across the width of the channel, rather than at a single site, they may provide a better areal representation of the bed material at that site.

Table 4.6 Particle size statistics of previous bed material surveys conducted by the Poverty Bay Catchment Board (now GDC).

km	1960					1956			1950		
	D_{25}	D_{50}	D_{75}	D_{90}	%sand	D_{50}	D_{90}	%sand	D_{50}	D_{90}	%sand
8.0	-	-	-	-	-	-	-	-	0.79	-	65
10.1	-	-	-	-	-	-	-	-	1.73	11.91	60
14.0	-	-	-	-	-	-	-	-	3.05	12.70	43
19.1	-	-	-	-	-	-	-	-	2.54	19.05	46
18.3	0.99	7.62	18.29	30.48	31	-	-	-	-	-	-
19.1	-	-	-	-	-	-	-	-	2.54	19.05	46
20.0	0.91	3.43	10.67	18.80	40	-	-	-	-	-	-
21.6	0.71	1.32	9.14	18.03	57	1.57	17.53	52	2.41	14.29	45
23.3	0.69	3.56	14.22	27.94	43	-	-	-	-	-	-
25.3	0.48	1.93	12.19	20.83	50	-	-	-	-	-	-
26.9	0.99	3.99	11.94	16.76	36	-	-	-	-	-	-
27.7	-	-	-	-	-	-	-	-	2.41	17.46	48
28.3	1.19	3.81	10.67	17.02	35	3.05	35.56	42	-	-	-
29.9	0.41	0.74	4.32	14.99	70	-	-	-	-	-	-
31.9	1.12	5.33	13.72	19.30	33	-	-	-	3.68	17.46	36
33.3	0.94	10.16	18.29	35.56	34	-	-	-	-	-	-
35.2	0.66	5.08	17.02	29.21	39	1.04	14.73	63	8.89	31.75	22
36.8	0.97	4.32	12.70	22.10	39	-	-	-	-	-	-
38.2	0.71	3.05	13.46	26.67	45	0.51	8.13	78	8.89	50.80	30
39.6	1.17	5.59	13.72	24.13	32	-	-	-	-	-	-
41.5	0.84	4.06	14.73	25.40	40	-	-	-	-	-	-
43.4	0.39	0.76	6.35	22.86	66	1.37	12.19	60	-	-	-
44.8	1.02	7.87	23.62	40.64	33	-	-	-	4.57	50.80	40
46.3	0.94	3.05	11.68	24.89	43	-	-	-	-	-	-
47.9	0.76	4.83	18.29	38.10	41	1.68	22.86	52	8.13	47.63	22
49.5	1.17	3.68	12.19	21.59	37	-	-	-	-	-	-
51.1	1.04	3.51	9.40	17.27	38	5.33	40.64	34	8.13	38.10	21
52.7	1.63	6.86	17.78	35.56	29	-	-	-	-	-	-
54.3	1.22	7.87	21.34	41.91	30	3.68	35.56	38	-	-	-
55.9	1.68	4.57	12.45	22.86	30	-	-	-	-	-	-
57.5	1.27	4.70	12.70	24.64	34	3.48	21.84	38	-	-	-
59.1	0.84	2.67	9.40	18.54	45	-	-	-	-	-	-
60.7	1.22	4.83	12.70	23.11	32	2.41	15.75	47	5.92	28.58	32
62.3	1.37	4.57	11.68	18.54	33	-	-	-	-	-	-
63.9	1.22	4.32	12.19	18.29	34	4.44	29.21	33	-	-	-
65.5	0.75	3.05	12.70	29.21	44	-	-	-	-	-	-
67.1	0.97	3.30	13.46	27.94	42	2.34	40.64	46	-	-	-
68.7	0.91	3.30	12.19	27.94	41	-	-	-	2.08	16.67	49
70.3	0.76	3.10	11.18	24.13	42	3.56	40.64	39	-	-	-
71.9	1.02	2.79	8.64	17.02	42	-	-	-	-	-	-
73.5	1.12	3.56	10.67	17.53	37	3.05	43.18	46	3.51	15.88	34
75.1	0.72	1.93	5.59	14.22	51	-	-	-	3.05	22.23	40
76.7	0.86	3.43	11.68	22.86	40	2.06	29.21	49	-	-	-
78.3	1.52	6.10	13.72	21.08	29	-	-	-	-	-	-
83.1	0.61	2.21	11.94	27.69	49	1.14	15.24	61	4.06	23.81	38
84.7	2.41	7.11	14.99	30.48	23	-	-	-	-	-	-
89.5	1.73	6.60	17.27	35.56	28	3.81	35.56	39	-	-	-
91.1	1.19	4.70	13.21	26.67	33	2.16	27.94	49	-	-	-
92.7	1.17	4.83	12.95	27.94	34	-	-	-	4.50	63.50	40
94.3	-	-	-	-	-	6.22	48.26	29	5.72	31.75	26
99.1	-	-	-	-	-	8.64	-	25	-	-	-

(-) Data not available

Particle shape; Particle shape statistics from each fifth bulk sampling site are presented in Table 4.7 (a-d).

Bed material lithology; The percentage of each lithology comprising the >16 mm fraction of each fifth bulk sample are presented in Table 4.8. Particle size statistics, including the mean b axes, as well as the maximum b axes for the > 16 mm particles of sandstone, siltstone and argillite are presented in Table 4.9.

Table 4.9 The maximum intermediate (b) axes, and the mean intermediate (b) axes from the >16 mm particle size fraction of each fifth bulk sample.

km	Average b axis			Maximum b axis		
	sst	zst	arg	sst	zst	arg
10	24	30	25	39	36	35
15	30	29	29	42	40	36
20	27	25	26	43	40	38
25	38	33	44	63	53	71
30	37	35	36	54	46	46
35	36	32	35	46	49	42
40	30	31	40	38	42	69
45	25	30	34	38	54	49
50	40	34	35	67	53	54
55	28	29	28	36	38	43
60	32	33	32	53	62	51
65	35	37	31	49	63	48
70	35	37	27	54	78	42
75	37	36	26	57	57	40
80	29	33	34	58	47	44
85	37	38	36	60	61	62
90	44	38	35	73	76	70
95	41	40	38	84	67	86
100	48	40	33	98	63	48

The trends observed in the particle size, shape and lithlology data presented in this chapter are described and interpreted in the following chapter.

Table 4.7a 16-22 mm pebbles.

	Disk Rod Index			Corey Shape Factor			Sphericity*		
km	sst	zst	arg	sst	zst	arg	sst	zst	arg
10	0.58	0.52	0.58	0.55	0.58	0.58	0.66	0.69	0.69
15	0.53	0.48	0.43	0.54	0.48	0.50	0.66	0.61	0.62
20	0.49	0.53	0.45	0.55	0.52	0.57	0.67	0.64	0.68
25	0.48	0.42	0.41	0.45	0.42	0.46	0.58	0.56	0.59
30	0.43	0.43	0.45	0.48	0.46	0.54	0.60	0.59	0.66
35	0.45	0.46	0.49	0.52	0.55	0.45	0.63	0.56	0.67
40	0.49	0.43	0.51	0.51	0.54	0.58	0.64	0.65	0.69
45	0.54	0.53	0.47	0.48	0.59	0.59	0.60	0.70	0.70
50	0.52	0.57	0.53	0.52	0.56	0.60	0.63	0.68	0.71
55	0.66	0.53	0.43	0.54	0.53	0.62	0.66	0.65	0.72
60	0.46	0.56	0.47	0.57	0.50	0.55	0.63	0.64	0.68
65	0.57	0.51	0.53	0.56	0.48	0.54	0.67	0.61	0.66
70	0.45	0.44	0.39	0.49	0.48	0.56	0.61	0.60	0.67
75	0.54	0.49	0.58	0.53	0.52	0.62	0.65	0.64	0.72
80	0.47	0.50	0.50	0.50	0.55	0.61	0.63	0.67	0.71
85	0.42	0.53	0.49	0.48	0.42	0.70	0.60	0.56	0.79
90	0.46	0.45	0.53	0.50	0.44	0.63	0.62	0.58	0.65
95	0.52	0.50	0.50	0.52	0.49	0.60	0.62	0.64	0.70
100	0.51	0.48	0.51	0.48	0.54	0.58	0.61	0.66	0.69

* maximum projection sphericity

(-) no pebbles present

Table 4.7b 22-31 mm pebbles.

	Disk Rod Index			Corey Shape Factor			Sphericity*		
km	sst	zst	arg	sst	zst	arg	sst	zst	arg
10	0.53	0.52	0.38	0.50	0.53	0.60	0.63	0.65	0.70
15	0.39	0.49	0.40	0.55	0.52	0.60	0.66	0.64	0.71
20	0.40	0.53	0.48	0.54	0.56	0.65	0.66	0.67	0.75
25	0.38	0.31	0.46	0.43	0.45	0.50	0.56	0.58	0.62
30	0.39	0.43	0.43	0.53	0.59	0.48	0.64	0.70	0.60
35	0.42	0.41	0.55	0.50	0.58	0.59	0.68	0.64	0.66
40	0.41	0.36	0.58	0.52	0.57	0.61	0.64	0.69	0.71
45	0.68	0.51	0.48	0.60	0.58	0.55	0.71	0.69	0.66
50	0.41	0.43	0.44	0.54	0.56	0.68	0.66	0.67	0.77
55	0.57	0.44	0.67	0.73	0.62	0.63	0.81	0.72	0.73
60	0.55	0.45	0.66	0.68	0.60	0.61	0.49	0.65	0.69
65	0.54	0.53	0.69	0.70	0.56	0.64	0.76	0.68	0.74
70	0.41	0.41	0.49	0.51	0.47	0.54	0.63	0.60	0.66
75	0.45	0.49	0.49	0.52	0.58	0.51	0.64	0.69	0.63
80	0.52	0.40	0.29	0.53	0.51	0.82	0.65	0.63	0.88
85	0.42	0.50	0.56	0.44	0.54	0.55	0.57	0.65	0.67
90	0.46	0.52	0.58	0.46	0.56	0.63	0.64	0.62	0.65
95	0.43	0.49	0.54	0.43	0.53	0.56	0.60	0.60	0.69
100	0.45	0.47	-	0.50	0.51	-	0.63	0.63	-

* maximum projection sphericity

(-) no pebbles present

Table 4.7c 31-45 mm pebbles.

	Disk Rod Index			Corey Shape Factor			Sphericity*		
km	sst	zst	arg	sst	zst	arg	sst	zst	arg
10	-	0.76	-	-	0.53	-	-	0.65	-
15	0.49	0.64	0.83	0.61	0.47	0.66	0.72	0.60	0.76
20	-	-	-	-	-	-	-	-	-
25	0.49	0.47	0.40	0.48	0.48	0.54	0.61	0.61	0.65
30	0.40	0.40	0.36	0.45	0.41	0.45	0.58	0.56	0.58
35	0.56	0.49	0.43	0.62	0.45	0.68	0.61	0.66	0.63
40	0.65	0.55	0.44	0.70	0.42	0.70	0.79	0.56	0.78
45	-	0.48	0.63	-	0.65	0.64	-	0.75	0.80
50	0.52	0.43	0.59	0.54	0.64	0.58	0.65	0.74	0.69
55	0.89	0.64	0.51	0.64	0.69	0.59	0.74	0.78	0.70
60	0.38	0.59	0.62	0.67	0.60	0.63	0.71	0.69	0.67
65	0.25	0.62	-	0.60	0.59	-	0.71	0.76	-
70	0.33	0.49	-	0.55	0.56	-	0.66	0.67	-
75	0.52	0.39	-	0.61	0.56	-	0.71	0.67	-
80	0.48	0.57	0.66	0.60	0.65	0.63	0.71	0.75	0.73
85	0.45	0.42	0.48	0.60	0.54	0.52	0.71	0.65	0.67
90	0.53	0.48	0.43	0.59	0.63	0.59	0.65	0.70	0.68
95	0.49	0.42	0.39	0.62	0.41	0.50	0.69	0.63	0.62
100	0.30	0.54	0.26	0.42	0.44	0.44	0.55	0.58	0.58

* maximum projection sphericity
(-) no pebbles present

Table 4.7d All pebbles >16 mm.

	Disk Rod Index			Corey Shape Factor			Sphericity*		
km	sst	zst	arg	sst	zst	arg	sst	zst	arg
10	0.56	0.6	0.48	0.53	0.55	0.59	0.64	0.66	0.69
15	0.47	0.54	0.56	0.57	0.49	0.59	0.68	0.61	0.7
20	0.45	0.53	0.47	0.55	0.54	0.61	0.66	0.66	0.71
25	0.52	0.4	0.42	0.51	0.45	0.53	0.63	0.58	0.65
30	0.5	0.43	0.52	0.57	0.56	0.56	0.67	0.67	0.67
35	0.53	0.46	0.5	0.55	0.54	0.61	0.64	0.65	0.69
40	0.51	0.45	0.42	0.58	0.51	0.65	0.69	0.63	0.74
45	0.61	0.51	0.55	0.54	0.61	0.62	0.66	0.71	0.73
50	0.42	0.55	0.55	0.47	0.59	0.59	0.6	0.7	0.7
55	0.66	0.53	0.43	0.64	0.61	0.61	0.74	0.72	0.72
60	0.53	0.56	0.47	0.61	0.59	0.58	0.69	0.66	0.71
65	0.46	0.54	0.58	0.62	0.55	0.63	0.72	0.67	0.73
70	0.48	0.45	0.44	0.56	0.49	0.55	0.67	0.62	0.67
75	0.56	0.52	0.36	0.59	0.59	0.56	0.7	0.7	0.68
80	0.46	0.49	0.5	0.56	0.54	0.7	0.67	0.66	0.79
85	0.46	0.51	0.5	0.51	0.5	0.58	0.64	0.62	0.69
90	0.47	0.52	0.43	0.54	0.52	0.55	0.61	0.63	0.65
95	0.49	0.52	0.46	0.56	0.47	0.56	0.59	0.6	0.67
100	0.45	0.49	0.38	0.52	0.45	0.51	0.64	0.58	0.64

* maximum projection sphericity
(-) no pebbles present

Table 4.8 The percentage of each lithology comprising the >16 mm particle size fraction.

	all size fractions >16 mm				16-22 mm size fraction				22-31mm size fraction				31-45 mm size fraction			
km	sst	zst	arg	other	sst	zst	arg	other	sst	zst	arg	other	sst	zst	arg	other
10	31.0	42.0	16.0	11.0	32.2	40.3	14.5	12.9	26.9	46.2	23.1	3.8	-	100.0	-	-
15	38.1	27.1	28.2	6.6	38.7	24.5	28.8	8.0	35.4	36.3	26.5	1.8	42.9	42.9	14.3	-
20	29.1	52.0	14.0	4.9	28.1	53.0	13.3	5.4	33.3	45.3	17.3	3.9	-	-	-	-
25	43.3	34.5	16.0	6.2	44.3	40.7	8.4	6.5	43.9	23.3	26.1	6.7	37.5	16.1	41.1	5.4
30	29.7	48.2	15.2	6.9	26.6	53.1	14.3	5.9	38.2	39.2	15.7	7.0	44.8	11.2	33.3	11.2
35	27.0	43.0	28.0	2.0	28.0	49.4	12.9	9.7	42.7	39.4	12.6	5.1	35.1	37.8	13.5	13.5
40	30.4	45.8	21.5	2.3	30.0	47.4	20.7	2.1	34.6	38.4	23.1	3.8	25.0	37.5	37.5	-
45	16.0	48.8	24.8	10.4	16.5	51.1	21.0	11.2	10.8	43.2	36.5	9.4	0.0	54.0	45.0	-
50	29.3	58.1	10.7	1.9	31.4	55.5	10.0	3.0	16.7	73.7	8.8	0.9	30.0	45.0	20.0	5.0
55	15.3	44.4	38.9	1.4	15.2	43.1	41.0	0.6	17.0	58.5	24.4	0.1	17.0	50.0	33.0	-
60	21.0	42.0	32.0	5.0	24.5	41.9	28.4	5.2	19.8	54.3	23.9	2.2	15.0	76.5	8.5	-
65	25.8	40.4	31.3	2.5	22.4	40.0	36.9	2.2	22.2	56.3	18.2	3.2	6.2	93.7	-	-
70	32.7	52.1	9.4	5.8	29.8	52.8	11.0	6.3	32.0	53.9	9.1	6.0	54.5	42.4	-	3.0
75	19.7	61.0	7.6	11.7	18.9	55.7	10.1	15.3	16.9	75.3	4.2	3.7	43.3	43.3	-	13.3
80	33.2	49.3	15.1	2.4	23.4	40.9	32.2	3.5	61.9	34.8	-	3.3	31.0	48.2	17.2	3.4
85	47.0	35.0	13.0	5.0	18.9	26.8	52.7	1.6	36.0	33.6	30.3	0.1	32.2	21.4	42.8	3.6
90	39.0	42.0	17.0	2.0	38.1	30.6	24.9	6.4	48.2	26.3	21.0	4.5	67.1	24.6	7.8	0.5
95	55.2	32.0	12.0	0.8	45.8	29.4	19.0	5.8	62.9	21.6	13.6	1.9	48.3	35.4	12.7	3.6
100	63.9	25.7	9.8	0.6	59.2	30.0	9.8	0.9	76.9	15.4	7.7	-	76.2	9.5	14.3	-

(-) no pebbles present

5.1 BED MATERIAL LITHOLOGY

The lithology of the bed material reflects the distribution of rock types within the source area, their relative resistance to abrasion, and the distance downstream from the sediment source (Miller, 1958; Plumley, 1948). In the Waipaoa River, the supply of sediment from the upper catchment was so great that the lithology of this supply dominated all particle size fractions of the bed material, throughout the length of the river. With the exception of Mangaorongo Stream, whose underlying geology is dominated by Miocene and Pliocene mudstone and sandstone, all tributaries of the upper catchment (above the gorge), supplied material comprised primarily of Cretaceous sandstone, siltstone and argillite. These three lithologies therefore dominated the bed material composition in the Waipaoa River.

Minor amounts (usually <5 % in total) of the bed material was comprised of other lithologies, and included limestone, calcite, chert, and mafic igneous intrusives. Mudstone or shale particles may have been of importance locally, but due to the soft nature of these lithologies, and once they were exposed to water, mudstone particles were rapidly broken down into mud and silt sized particles. Mudstone was supplied to the channel by bank erosion from bluffs and cliffs adjacent to the river. Rarely was mudstone encountered farther than 1 km downstream from the sediment input.

Bed material from the Waingaromia, Waihora and Waikohu rivers in the middle reaches of the Waipaoa River exhibited distinct lithologies. The drainage basins of these streams were underlain predominantly by the Te Arai Formation. The Te Arai Formation includes a mafic igneous conglomerate member that consists of gabbro, diorite and pyroxenite boulders (Mazengarb *et al.*, 1991). Mazengarb *et al.* (1991) observed that a possible source for these boulders was from the Matakaoa Basalt Sequence. Bed material from the Waingaromia and Waihora streams both exhibited considerable amounts of basaltic particles, and the Waikohu Stream exhibited particles comprised of diorite, pyroxenite and gabbro. None of these lithologies were encountered in the Waipaoa River bed material. This suggests that either the bed load from these tributaries was not transferred to the Waipaoa River, or that these distinct lithologies were diluted to such an extent that they were not encountered in the main channel. Each of the tributaries underwent a transition from a gravel-bed to a sand-bed channel near their confluence with the Waipaoa River, which possibly prevented the transfer of the gravel particle size fractions to the main stem Waipaoa River.

The basalt, pyroxenite, diorite and gabbro pebbles in the bed material of the Waingaromia, Waikohu, and Waihora rivers were mechanically durable, and were relatively more resistant to abrasion than the sandstone, siltstone, and argillite supplied from the upper reaches. It was not likely therefore that these rock types were rapidly abraded during transport in the Waipaoa River. Sample sizes were large enough to be representative, and it was not likely that these rock types were missed by bulk sampling.

The percentage of the principal rock types comprising the >16 mm fraction of the Waipaoa River bed material are graphically presented in Figures 5.1 (a-d). No consistent downstream trends were observed for any lithology, instead the percentage of each lithology in the bed material fluctuated considerably with distance. No lithology was present in consistently greater proportions, or increased in percentage downstream at the expense of other rock types. The relatively greater percentage of sandstone in the upper 5-10 kilometres reflected the close proximity of the sampling sites to tributary streams draining catchments that were predominantly underlain by the Tikihore Formation. The highest percentage of sandstone was encountered at the 100 km sampling site, situated a few hundred metres downstream from the Tikihore Stream, from which the Tikihore Formation takes its name.

In addition to the statistics obtained for sandstone, siltstone and argillite pebbles, the percentage of pebbles composed of 'soft' lithologies, that included sandstone, mudstone, and siltstone are presented in Figure 5.2. The pebble lithologies were considered to be 'soft' if they could be scratched with a finger nail, or a plastic ruler. Soft pebbles generally comprised 5-10 % of the total particles >16 mm, and were included in the percentages of

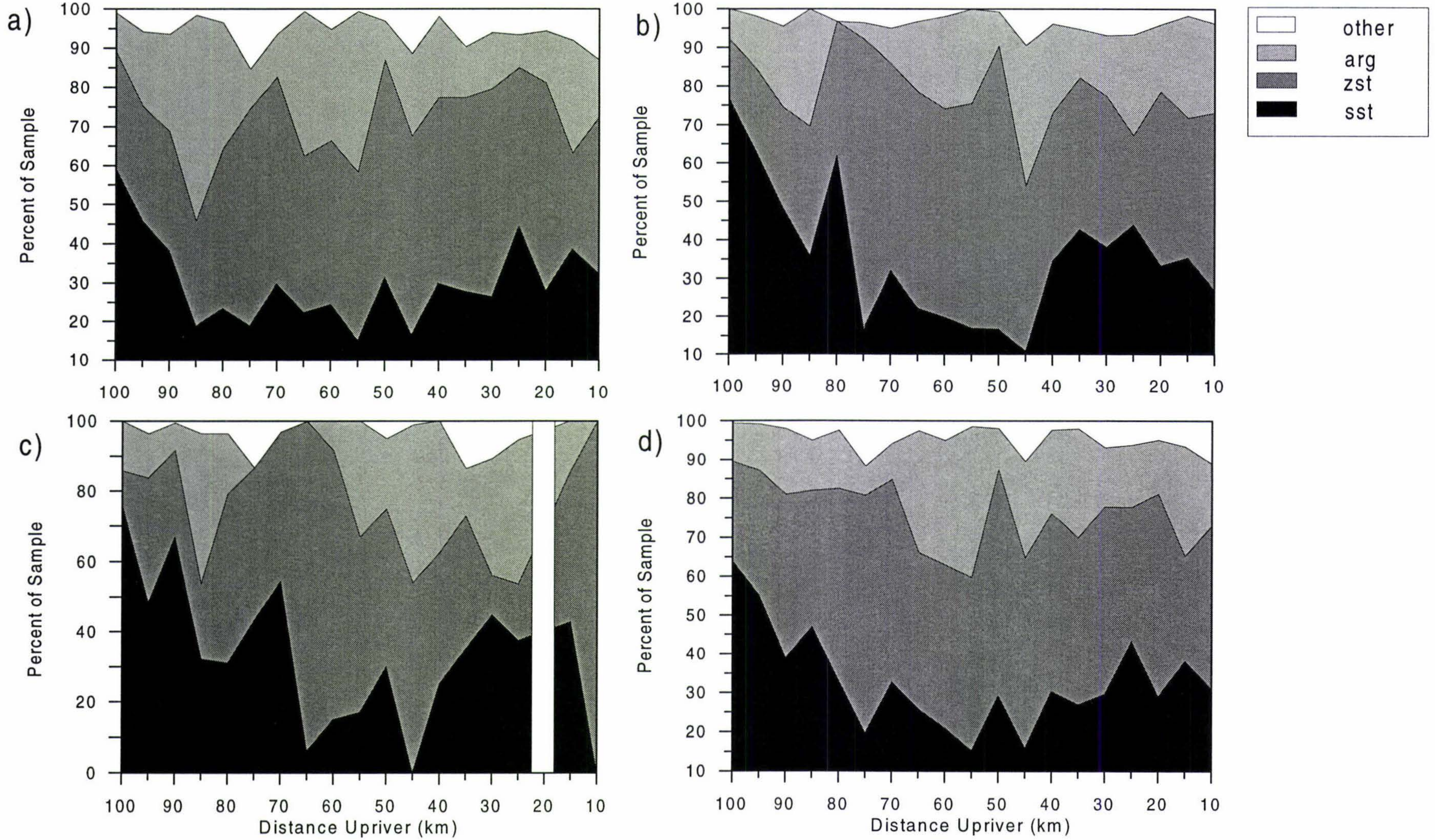


Figure 5.1 The downstream variation in the percentage of the main lithologies in the a) 16-22 mm, b) 22-31 mm, c) 31-45 mm, and d) >16 mm particle size fractions in the Waipaoa River bed material.

sandstone, siltstone and argillite particles presented earlier. The proportion of soft particles in the subsurface bed material fluctuated considerably with distance, however, the soft particles exhibited a much greater rate of downstream decline in the sample percentage, compared to the other lithologies. Downstream of ~ 50 km, the proportion of soft particles declined to <2.5 % of the total > 16 mm particle size fraction. This marked decline was coincident with the location in the river at which an extensive floodplain was developed (near Te Karaka). The decline in the percentage of 'soft' lithologies was attributed to the diminished supply of soft mudstone from bluffs and hill slopes that were directly linked to the channel. It is proposed that these soft lithologies were rapidly abraded during fluvial transport, and that the presence of these particles in the bed material was dependent upon the constant supply of soft mudstone from bank erosion in the middle reaches.

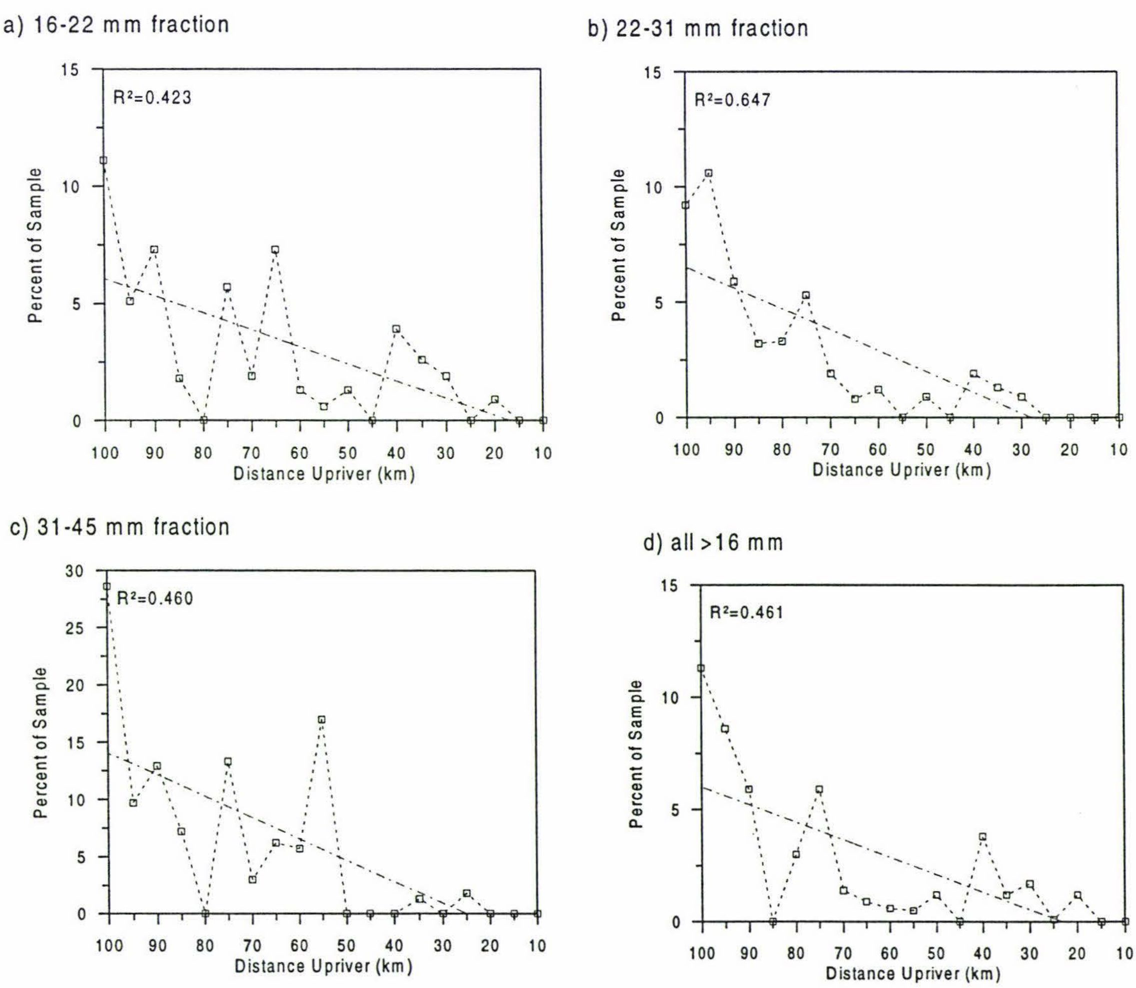


Figure 5.2 The percentage of 'soft' lithologies encountered in the a) 16-22 mm, b) 22-31 mm, c) 31-45 mm, and d) >16 mm particle size fractions.

The longitudinal variation in the average b-axes from each > 16 mm particle size fraction, of each lithology is shown in Figure 5.3. Fining coefficients for sandstone, siltstone, and argillite pebbles, calculated over the gravel-bed portion of the Waipaoa River are presented in Table 5.1. The fining coefficients were calculated by the method employed by Shaw and Kellerhals (1982). All rock types decreased in size by a similar percentage, and exhibited comparable rates of diminution downstream. The percentage decline in mean intermediate axis for sandstone was 39.1 %, siltstone was 26.9 %, and argillite was 26.6 %, based on the difference in average b axis between the upper reaches (90-100 km), and the lower reaches (10-20 km).

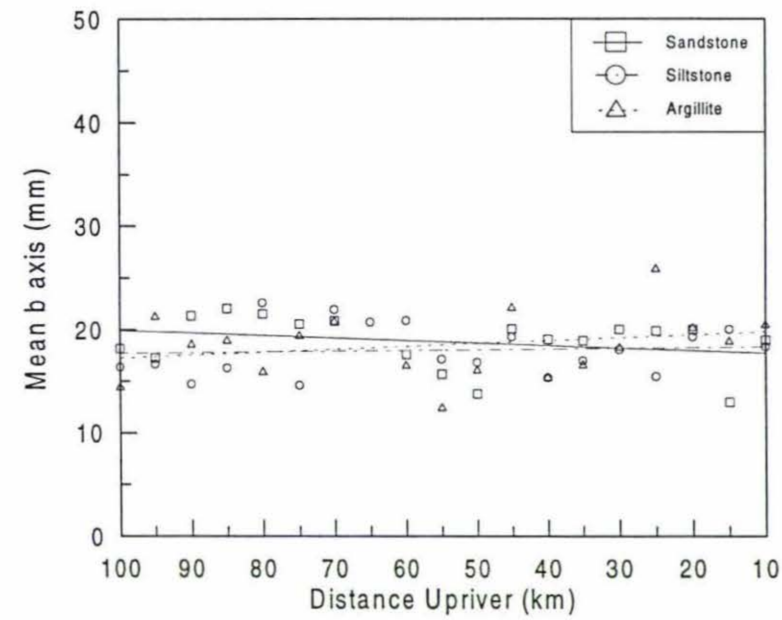


Figure 5.3 The mean intermediate axes from each fifth bulk sample, from all pebbles >16 mm.

The longitudinal variation in the maximum measured intermediate (b) axis of sandstone, siltstone and argillite particles are presented in Figure 5.4. A greater degree of variation was exhibited by the maximum b axes, than was observed for the mean b axes. The greater degree of variation probably was due to the chance inclusion or omission of one particle of a particular lithology from the bulk sample. In general, the maximum particle size of all three lithologies reflected the maximum particle size of the entire sample. No lithology exhibited a consistently larger maximum particle size, and the maximum b axes were similar for sandstone, siltstone and argillite pebbles at a single sampling site. The percentage decline was greater for the maximum b axis, than for the mean b axes, and the

Table 5.1 Fining coefficients obtained for each of the three main lithologies. The method employing the mean b axis of >16 mm pebbles, and the D_{50}, appear to give the most consistent results.

	Fining Coefficient		
Lithology	D_{50}	D_{90}	mean b
Sandstone	0.0017	0.0041	0.0041
Siltstone	0.0036	0.0006	0.0035
Argillite	0.0026	0.0003	0.0031[1]

[1] excluding coarse inputs between 50 and 25 km

maximum b axes of all lithologies decreased downstream by similar proportions. The maximum b axes of sandstone particles decreased by 51.4 %, siltstone particles by 43.7 %, and argillite particles by 46.6 % in the downstream direction.

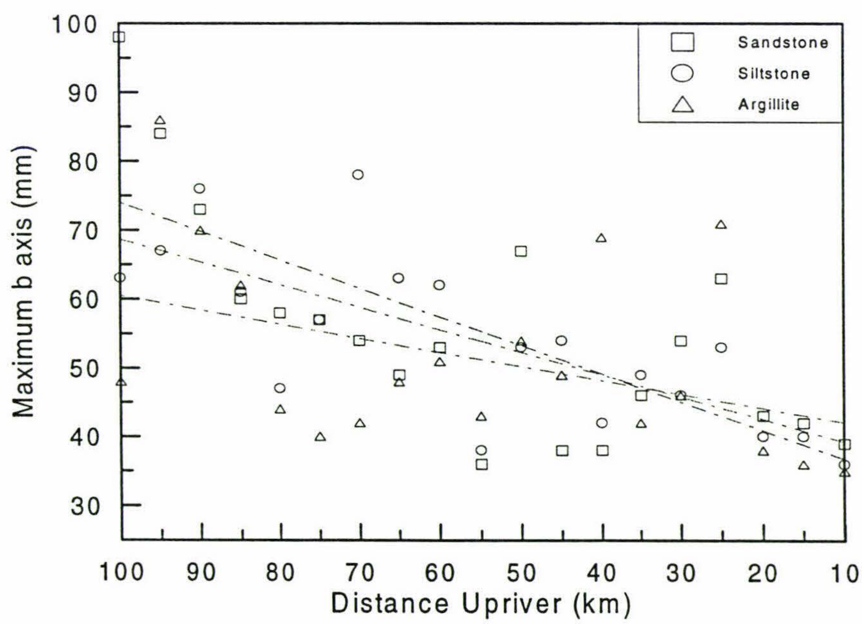


Figure 5.4 The maximum intermediate axes from each fifth bulk sample, from the >16 mm particle size fraction.

5.2 Structure and Composition of the Bed Material

The subsurface bed material of the Waipaoa River typically consisted of 55-65 % gravel, 25-35 % sand, and 5-10 % fines (<250 μ; fine sand, silt and clay). The proportion of gravel, sand and fines varied depending upon the position in the river, but in general, the percent sand and fines increased downstream at the expense of the percent gravel. The percent gravel, sand and fines in the subsurface bed material of the Waipaoa River are shown in Figure 5.5. The unusually high proportion of fine material (<250 μ) for a gravel bed river, is accounted for by the nature of the sediment supply to the headwater reaches. The headwater reaches were primarily supplied with fine grained material from the erosion of argillite and siltstone terrains. A high proportion of fines was present in the upper reaches of the Waipaoa River, and the proportion decreased downstream of the braided reach, and subsequently increased again in the lower reaches.

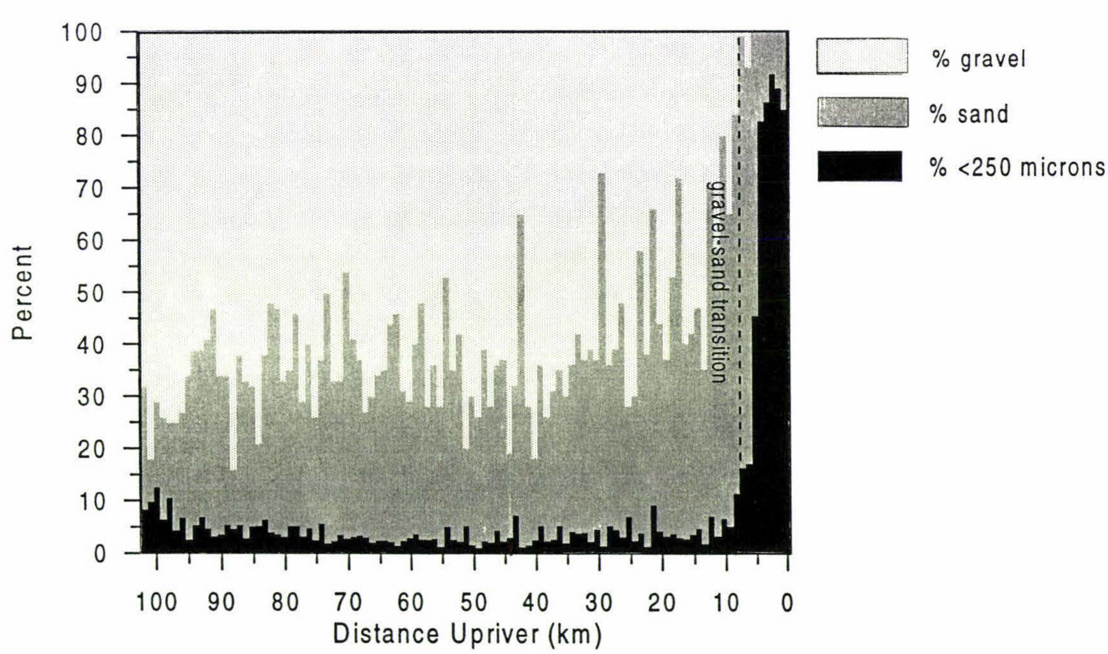


Figure 5.5 Longitudinal variation in the percentage of fines, sand and gravel in the Waipaoa River bed material. Fines include all particles <250 microns in diameter.

The percentage of fines in the subsurface bed material exhibited a linear decrease with distance from 102-92 km, followed by an exponential decrease downstream from 92 km to the mouth. However, the greatest rate of increase was downstream from 8 km, where the percentage of fines increased from ~10 % to ~90 % at the river mouth. The percent sand in the subsurface bed material exhibited a logarithmic increase from 102 to 8 km, and downstream of the gravel-sand transition, the percent sand decreased according to a power function from ~60 % at 10 km, to ~10 % at the river mouth. At ~8 km from the river mouth, the Waipaoa River underwent a rapid transition from a gravel-bed to a sand-bed channel. The percent gravel decreased by a power function from 102 to 8 km, followed by a linear decrease downstream from 8 km to the coast.

A high proportion of fine material is carried by the Waipaoa River, consequently, the bed material typically was matrix supported. Fine and coarse material, therefore, were deposited simultaneously. The mechanism of deposition in the Waipaoa River was expected to differ slightly from that of channels exhibiting clast supported gravel deposits, in which the fine particles are presumed to infiltrate between the coarse particles after bed load transport has ceased (Church *et al.*, 1987). Particles <250 μ, however, may have been deposited between the gravel and sand particles in this manner, as the Waipaoa River carries a high suspended sediment load. Matrix supported gravel mixtures often do not exhibit well-defined bimodal particle size distributions, that are often observed in clast-supported gravel deposits (for example; Shaw & Kellerhals, 1982) (Church *et al.*, 1987), and the particle size distributions obtained from the subsurface bed material in the Waipaoa River characteristically exhibited polymodal particle size distribution curves.

5.3 PARTICLE SIZE TRENDS

In the Waipaoa River, the size of the bed material was intimately related to the durability of the sediment inputs, through the controlling influence of the physical properties of each lithology; such as hardness, resistance to abrasion and desiccation, brittleness, and resistance to solution (eg. limestone). Bed material size at any point in the river also was related to the distance of fluvial transport from the headwaters, as well as from the individual sediment inputs. The bed material particle size also is related to the sediment transporting capacity of the river. The sediment transporting capacity of the river is associated with the river morphology, among other things, which underwent a series of changes in the downstream direction.

Subsurface bed material; Over the length of the Waipaoa River, from 104 km to a point 10 km from the coast (a length of 94 km), the D_{90} declined from ~48 mm to ~6 mm, where the D_x represents the particle diameter (D in mm) at which x % of the sample was finer. Over the same distance, the median grainsize (D_{50}) declined from ~6 mm to ~2 mm (refer to Figure 5.6). Figure 5.7 illustrates the longitudinal variation in each of the measured particle size percentiles (D_5-D_{95}), and demonstrates that fining occurred across the entire particle size distribution. However, the fastest rates of downstream fining were observed in the coarser particle size fractions, and is best illustrated by employing a linear particle size scale (Figure 5.7a).

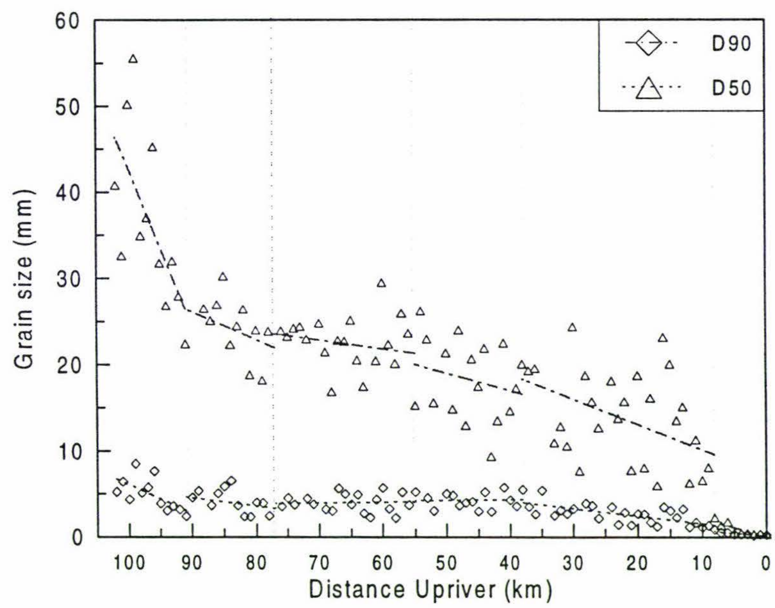


Figure 5.6 Longitudinal variation in the subsurface D_{50}, and D_{90}. Regression lines were drawn by least squares regression analysis.

The D_5, representing the finest 5% of the particle size distribution curve, exhibited a slight trend of downstream coarsening, and is best illustrated by employing a logarithmic particle size scale (Figure 5.7b). The D_5 was slightly finer in the upper reaches, above the gorge, than it was at the river mouth. This appears counter-intuitive, until consideration of the processes occurring in the Waipaoa River are taken into account. The D_5 represents the silt-clay fraction of the bed material, and in most gravel-bed rivers is considered to be the product of abrasion of the gravel clasts during fluvial transport (Kuenen, 1956). In the upper reaches of the Waipaoa River, the supply of fine grained material from gully and mass movement erosion ensures that a large quantity of fine material is supplied to the river channel at the source. The relatively finer D_5 in this reach was a reflection of the sediment supply. However, the initial rapid breakdown of unsound particles in the first few kilometres of fluvial transport also contributed to the high proportion of fine material, and therefore the finer D_5 in the upper reach.

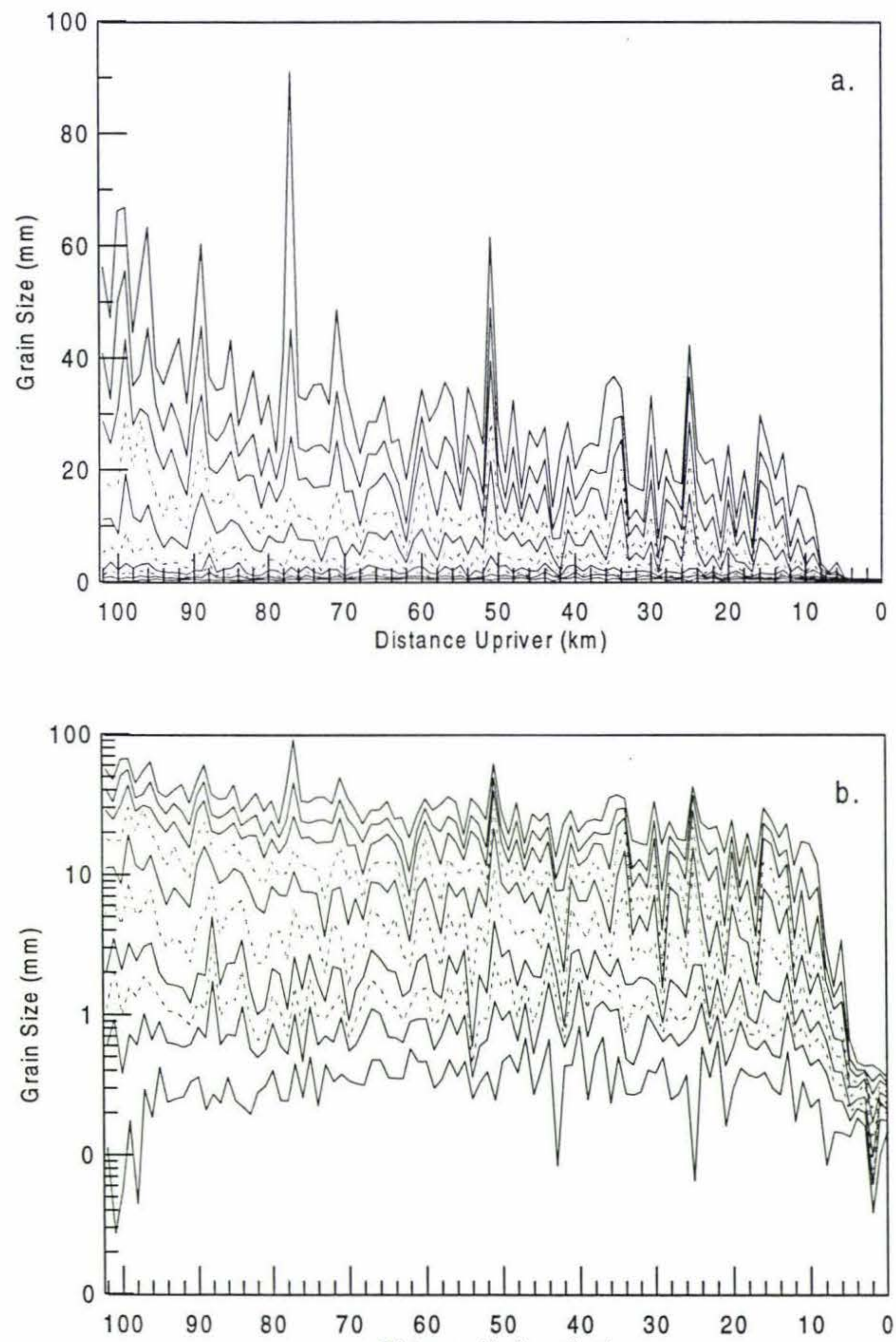


Figure 5.7 Longitudinal variation in all calculated percentiles, a) employing a linear particle size scale, and b) employing logarithmic particle size scale. The dashed lines represent the D_{25}, D_{50}, and D_{75}, respectively, from the base.

The relatively fine median particle size (~6 mm) in the upper reaches of the Waipaoa River also reflects the large quantity of predominantly fine grained material that is supplied to the channel in the upper reaches. Consequently, the median particle size was relatively fine over the length of the Waipaoa River and suggests that the particle size fractions finer than the median particle size were transported through the Waipaoa River system with limited modification by selective transport and abrasion processes.

Interruptions to the general trend of downstream fining in the Waipaoa River mostly can be related to sediment inputs that enter the channel directly from the erosion of bluffs, cliffs, hill slopes, or the channel banks. Sediment inputs adjacent to the sediment sampling sites are listed in Table 5.2. Coarse peaks generally can be related to the input of sediment from actively eroding bluffs and cliff faces (eg. 77 km), or terrace gravels from low terraces adjacent to the river (eg. 51 km). In the upper reaches, coarse sediment inputs originated from tributary streams, as well as from mass movements that were transferred directly to the channel (eg. 103 km). Figure 5.8 illustrates a small alluvial fan that had formed by a mass movment directly into the Waipaoa River channel, at 103 km.

Figure 5.8 Small alluvial fan that had formed in the Waipaoa River channel as a result of a mass movement in a hillslope underlain by the Mangatu formation, at 103 km.

Table 5.2 Sediment inputs adjacent to the sediment sampling sites in the Waipaoa River.

km	Description	Sediment type
104-94	Large alluvial fans from tributary streams and gully systems adjacent to the river channel	fine and coarse
103	Mass movement directly into channel	fine & coarse
102	Mid-channel island eroding	coarse cobbles (& concretions)
100	Active gullies in the channel banks	predominantly fine
91-82	Crushed mudstone, and alternating mudstone/sand-stone bluffs with scree slopes at base, triangular gully chutes direct sediment into the channel	fine and coarse
88	2 large mass movements (mudstone)	predominantly fine
77	Alternating mudstone/sandstone bluff, contains concretions	predominantly coarse
74	Mudstone bluff	predominantly fine
71 & 72	Crushed mudstone bluffs with scree slopes at base	predominantly fine
70-69	New channel, formed during Cyclone Bola	fine and coarse
70-62	Crushed mudstone bluffs with scree slopes at base	fine
51	Terrace gravels eroded from adjacent terrace, mid-channel island has formed at the same level	coarse
36	Cliff face, alternating mudstone/sandstone	fine and coarse
19	Channel bank slump	fine
6-10	Gravel lenses within floodplain deposits	fine-medium gravel plus sand

The tributary streams of the upper reaches (above the gorge) exhibited steep alluvial fans at their confluence with the Waipaoa River. The Mangaorongo Stream of the upper reaches, however, did not exhibit a steep alluvial fan at its confluence with the Waipaoa River. This was a reflection of the underlying geology in the catchment. The Mangaorongo Stream catchment is underlain by poorly consolidated mudstone and sandstone of the Te Arai and Tokomaru Formations. Particle size distribution curves for the tributaries in the upper reaches are presented in Figure 5.9. The particle size distribution obtained from the Mangaorongo Stream exhibited pronounced bimodality, with prominent peaks in the coarse gravel and silt particle size ranges. Gully complexes, directly coupled to the Waipaoa River channel, also exhibited steep alluvial fans that extend into the Waipaoa River channel. These alluvial fans can be considered as non-fluvial sediment storage controls, and may promote local sorting of the bed material (Rice, 1994). Distinct alluvial fans that originated from (1st order) gully complexes and that impinged on the Waipaoa River channel were present at 95 km, and at 98 km (Figure 5.10). Mass movements also were common in the upper reaches, and through the gorge. Small alluvial fans extending into the river were observed where the mass movements were directly transferred from the bluffs and hill slopes to the river channel (Figure 5.11).

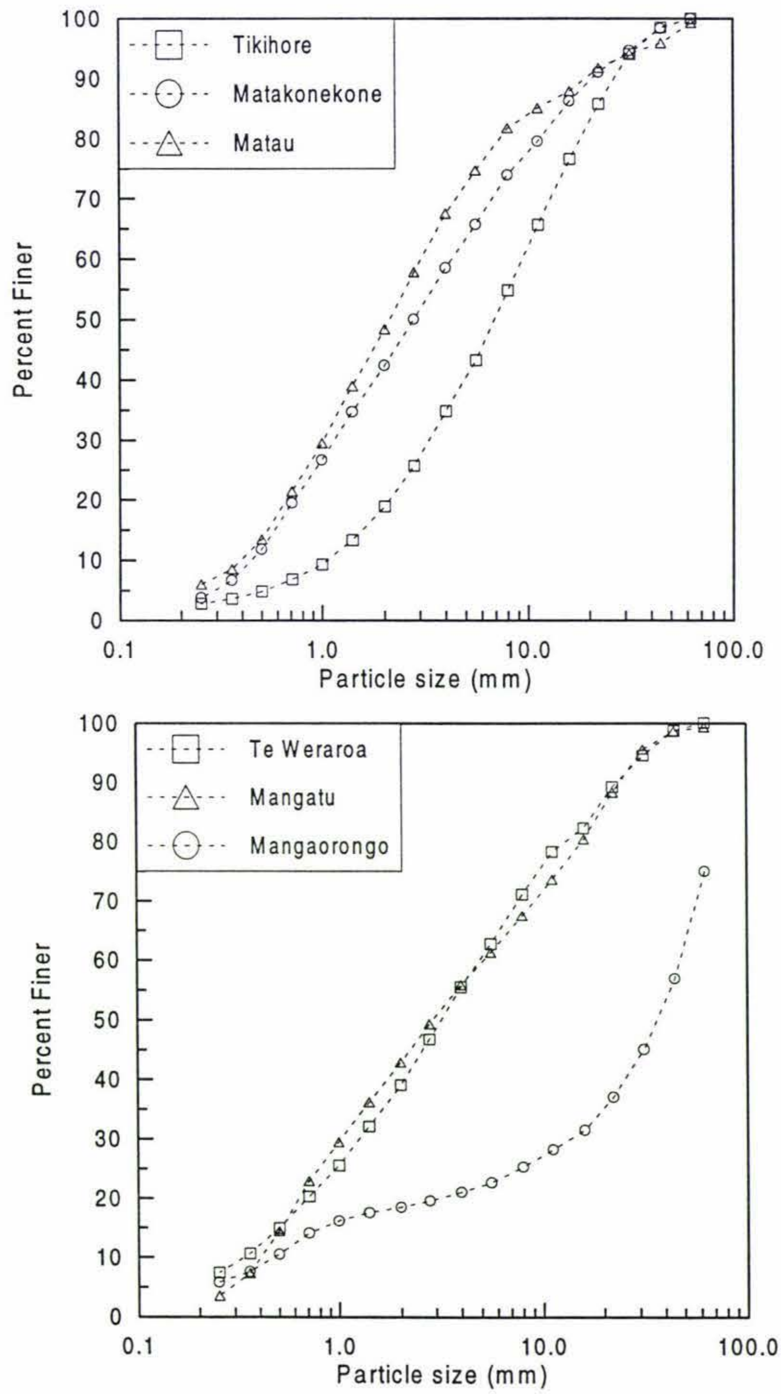


Figure 5.9 Particle size distribution curves from the bulk samples from the tributary streams in the upper reaches. The particle size distribution curves from a) Tikihore, Matakonekone, and Matau streams, b) Te Weraroa and Mangaorongo streams, plus the Mangatu River.

Figure 5.10 Large alluvial fan at the mouth of Gully 117, at 98 km. Note that the Waipaoa River has trimmed the fan perimeter, indicating that the fan is no longer active.

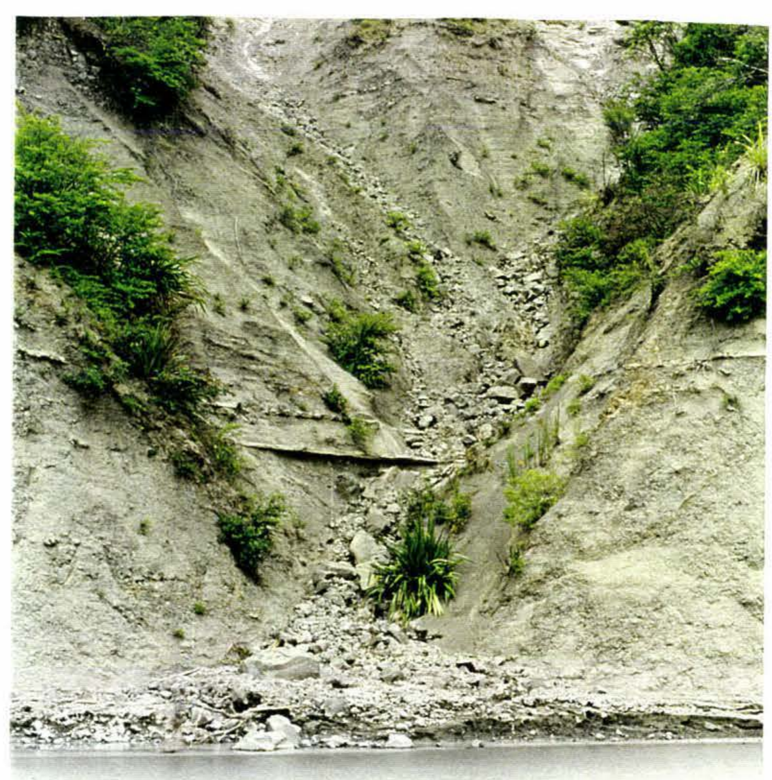


Figure 5.11 A typical mass movent in the gorge reach, that was transferred directly from the adjacent bluff to the Waipaoa River.

The Mangatu River is the largest tributary of the Waipaoa River, and joins the river at 76 km. The Mangatu River also is a braided gravel bed river, and is supplied with large quantities of fine grained material from argillite and siltstone terrains. Consequently, the particle size of the bed material in the Mangatu River is very similar to that in the Waipaoa River. Comparison of the particle size distributions in the Waipaoa River, with that in the Mangatu River suggest that the particles size fractions from 0.025 mm to 2 mm were relatively enhanced downstream of the confluence.

In the Waipaoa River, most fine peaks of the bed material size distribution were accounted for by inputs of crushed argillite and mudstone from bluffs and cliffs in the upper and middle reaches. In the lower reaches, bank erosion of fine flood-plain sediments resulted in bed material samples that were finer than the general trend. A notable drop in average particle size was observed downstream from the confluence with Te Weraroa Stream (at 94 km). Te Weraroa Stream supplies a high proportion of fine material derived from the large gully complexes within the catchment, such as the Tarndale Gully (Banbury, 1996). The particle size distribution obtained from Te Weraroa Stream is compared to the particle size distributions from the Waipaoa River above and below the confluence with Te Weraroa stream in Figure 5.12.

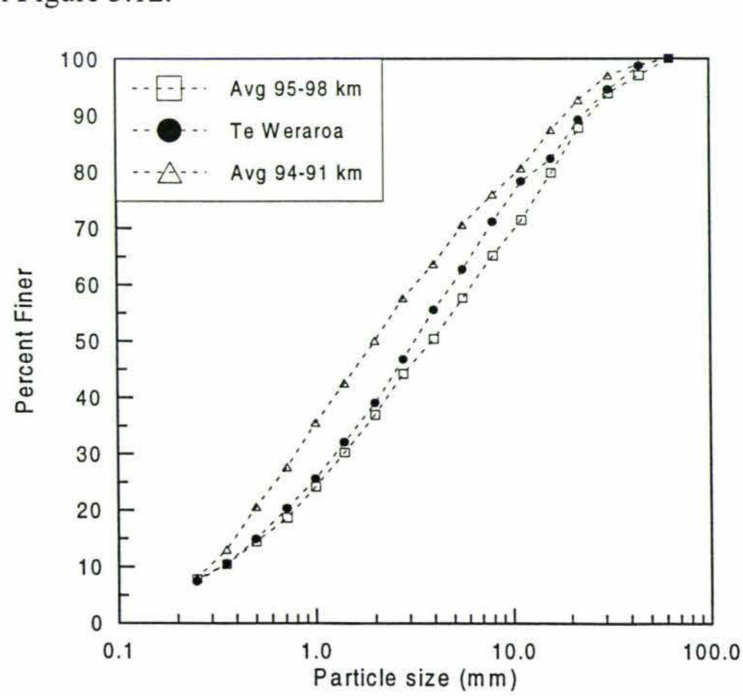


Figure 5.12 The particle size distribution curves from the Waipaoa River above and below the confluence of the Te Weraroa stream, and compared to the particle size distribution curve from Te Weraroa Stream.

The Waingaromia, Waikohu, and Waihora rivers in the middle reaches of the Waipaoa River also are gravel-bed streams, but their sediment loads predominantly are comprised of suspended sediment. The particle size distributions obtained from these tributaries are presented in Figure 5.13. Unlike the particle size distributions obtained for the subsurface bed material in the main-stem Waipaoa River, the particle size distributions obtained from the Waingaromia, Waikohu, and Waihora streams exhibited pronounced bimodality. Similar prominent particle size modes were encountered in each of these tributaries. The particle size modes were centred in the pebble (11.2-16 mm), and medium sand (0.355-0.25 mm) particle size ranges. The bed material deposits were densely packed, clast-supported gravels, that had the appearance of gravels that were not often transported. The gravels appeared 'dirty', compared to the relatively 'clean' gravels of the main-stem Waipaoa River. No influence was observed in the particle size of the Waipaoa River bed material in the middle reaches downstream from these tributaries. Insignificant quantities of the gravel fraction in the bed material in these tributaries appeared to be transferred to the Waipaoa River. No alluvial fans were present at the mouths of these tributaries, instead water appeared to be ponded near the confluence. The mouth of the Waingaromia River was blocked by a lateral bar in the Waipaoa River.

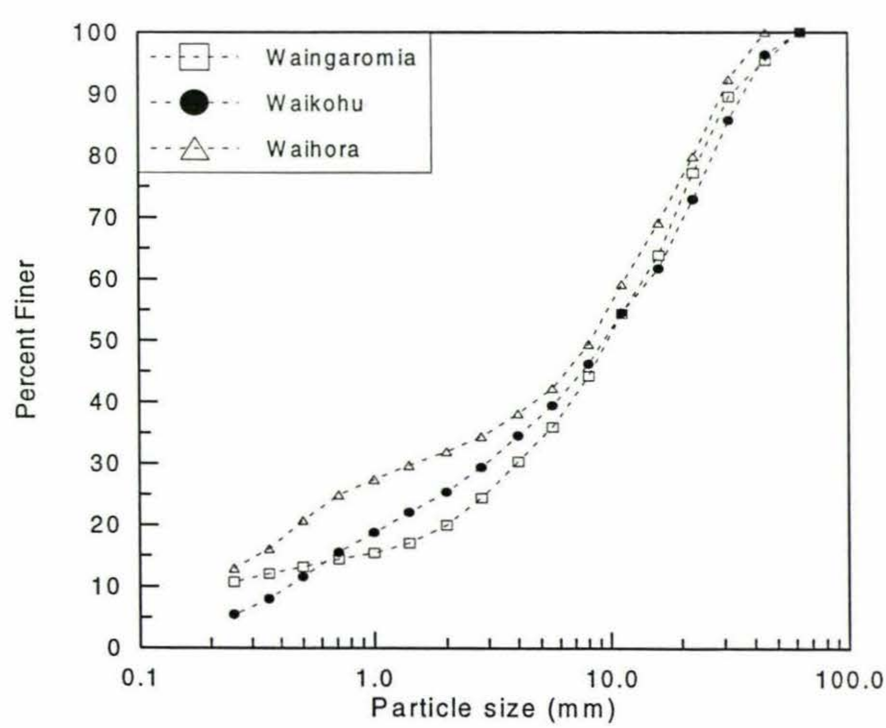


Figure 5.13 Particle size distribution curves from the tributaries in the middle and lower reaches of the Waipaoa River. All tributaries in these reaches exhibited distinct bimodality.

The Waingaromia, Waikohu, and Waihora rivers all exhibited a back-water effect near their confluence with the Waipaoa River. The faster rate of bed level aggradation, plus the faster water velocity in the main channel probably resulted in a backwater effect being established within each tributary. Ponding of water was witnessed near the mouths of the Waihora, Waikohu and Waingaromia streams, and no gravel was observed on the bed, although no samples were taken to confirm this. Samples were, however, obtained 5-10 kilometres upstream from the stream confluences, where the backwater effect was no longer present and exposed stream bed was accessible. The bed material obtained from all three rivers exhibited pronounced bimodality, consequently, similar gravel-sand transitions are expected to occur near the confluence of these tributaries with the main channel.

Sediment inputs from bank erosion in the Waipaoa River generally had a localised effect. Fine or coarse material may have influenced the bed material of the bar in the immediate vicinity of the sediment input, or the following bar downstream, but there did not appear to be any influence in subsequent downstream bed material samples. This suggests that the fine sediment inputs were rapidly incorporated into the bed load or suspended load, and transported through the river system, but coarse sediment inputs were not entrained, and remained in the immediate vicinity of the sediment input. Coarse sediment transferred directly to the channel from the hill slopes may be subsequently broken down by physical weathering processes while exposed on the bar surface (Figure 5.14), and the products easily entrained. Coarse particles were observed in various weathered states on the surface of bars adjacent to sediment sources.

Surface bed material; The longitudinal variation of all particle size fractions obtained by grid-by-number sampling in the Waipaoa River are presented in Figure 5.15. Figure 5.15 illustrates that downstream fining also was manifest in all particle size fractions of the surface bed material. However, no clear distinction can be made between different particle size fractions of the surface bed material, and all particle size fractions declined in size downstream at a similar rate. The longitudinal variation of the surface D_{50} and D_{90} are portrayed in Figure 5.16. The surface D_{90} declined from 53.4 mm in the headwater reaches, to 19.9 mm in the reach upstream of the gravel-sand transition. The D_{50} correspondingly declined from 20.6 mm, to 5.2 mm over the same distance.

Figure 5.14 A desiccated siltstone particle on the surface at 77 km, adjacent to a coarse sediment input.

Bar surfaces in the Waipaoa River often exhibited an armour layer (Figure 5.17). The grainsize distribution of the armoured surface was typically 1.44 (± 0.196) times coarser than the underlying bed material. However, the surface and subsurface bed material differed by a maximum factor of 2.79, and a minimum factor of 0.66. Church *et al.* (1987) deduced the processes which lead to the formation of the armour layer by plotting surface D_{50} versus subsurface D_{50}, which had been truncated at the same lower particle size limit as the surface sample. If the surface grain size distribution simply was a truncated version of the subsurface material (*ie.* $D_{50\ surface} = D_{50\ subsurface}$), the armour layer was assumed to be the product of the winnowing of fine material from between the gravel clasts. If, however, the surface layer was consistently coarser than the subsurface (*ie.* contained larger particles), the armour layer was assumed to be a product of equilibrium transport, in which the coarsest particles were concentrated at the surface. A plot of $D_{50\ surface}$ versus $D_{50\ subsurface}$ of bed material from the Waipaoa River (Figure 5.18) indicates that the majority of the armoured surfaces sampled were formed by equilibrium transport, and spatial concentration of the largest particles at the surface. The points falling below the truncation line indicate that the surface bed material was finer than the underlying bed material. In most cases, this occurred in situations where the armour layer had been disturbed by cattle.

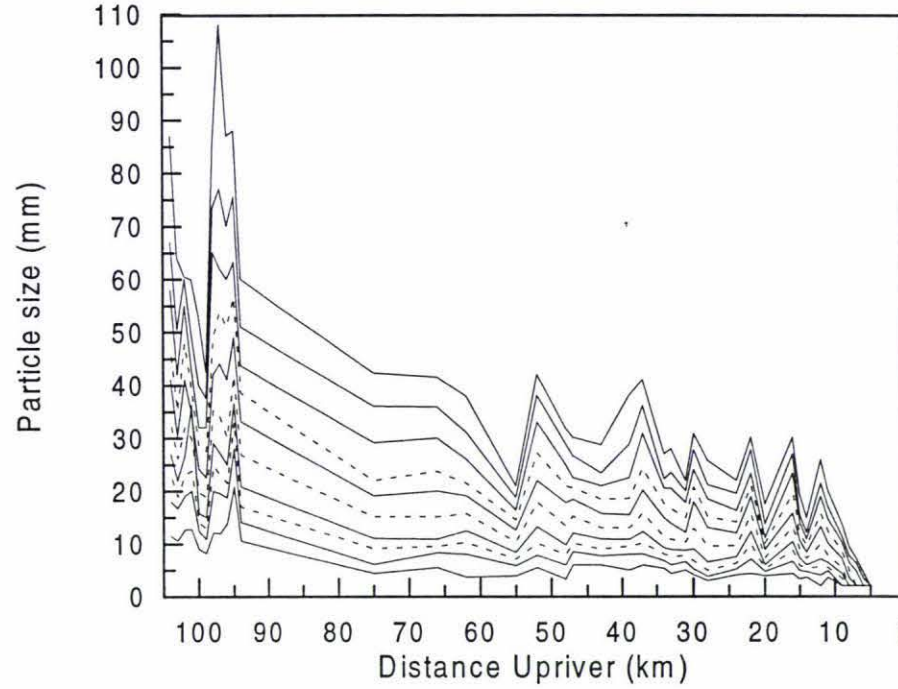


Figure 5.15 Longitudinal variation in all measured particle size percentiles from grid-by-number sampling. The dashed lines represent the D_{25}, D_{50}, and D_{75}, respectievly, from the base (note: no samples were obtained between 75 and 93 km).

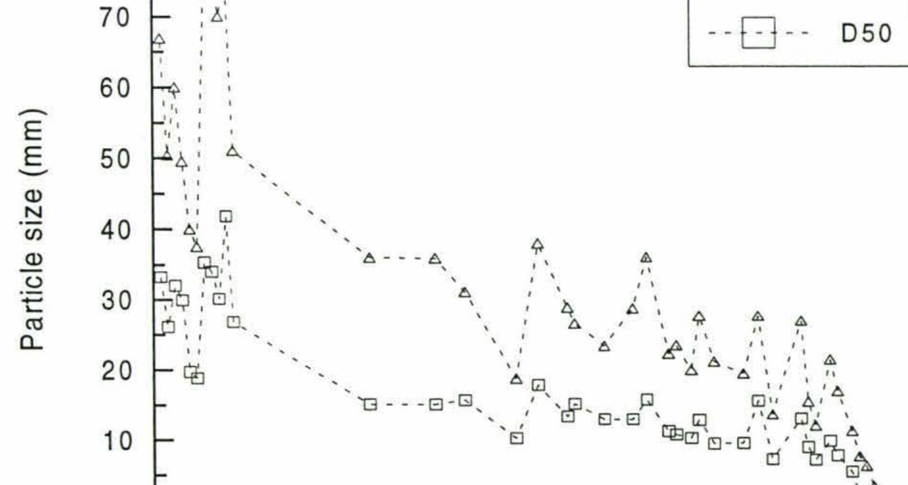


Figure 5.16 Longitudinal variation in the surface D_{50}, and D_{90} (note: no samples were obtained between 75 and 93 km).

Figure 5.17 A typical armoured surface at 76 km, in the middle reaches of the Waipaoa River (Dec 1996).

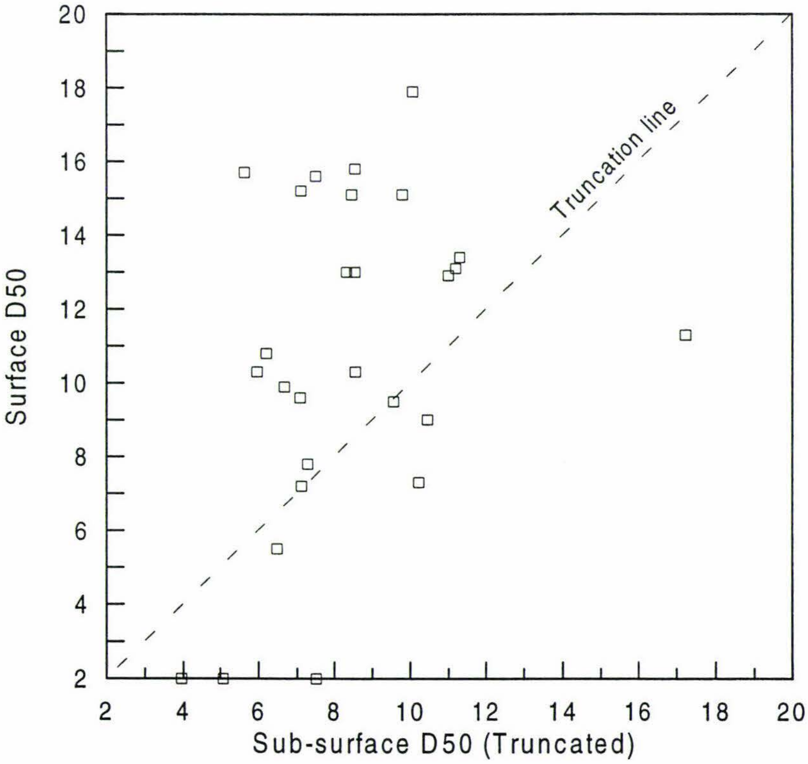


Figure 5.18 Relationship between surface D_{50} and truncated subsurface D_{50}. The points falling near the truncation line are assumed to be the product of winnowing. Surface and subsurface sediment samples were truncated at 3 mm.

Although armoured surfaces were present for the majority of the length of the Waipaoa River, armour layers exhibited significant patchiness at the bar scale, and often encompassed only a few square metres. An armour layer was absent in the upper reaches above the gorge, and became more prevalent throughout the middle reaches. In the lower reaches, armoured surfaces became increasingly patchy and scarce.

The downstream variation in the median particle size in the surface and subsurface sediment populations are compared in Figure 5.19. The processes that lead to downstream fining in the surface and subsurface sediment populations in the Waipaoa River are separate and distinct. The bed material in the Waipaoa River probably has not experienced widespread mobilisation since Cyclone Bola, in March 1988. Only three floods of significance have occurred since March, 1988. The floods occurred in September 1988, October 1990, and March 1996 (Walpole, personal communication 1997), but the discharge experienced was insufficient to promote extensive bed load transport. The March 1996 flood occurred after completion of the bed material sampling. The subsurface bed

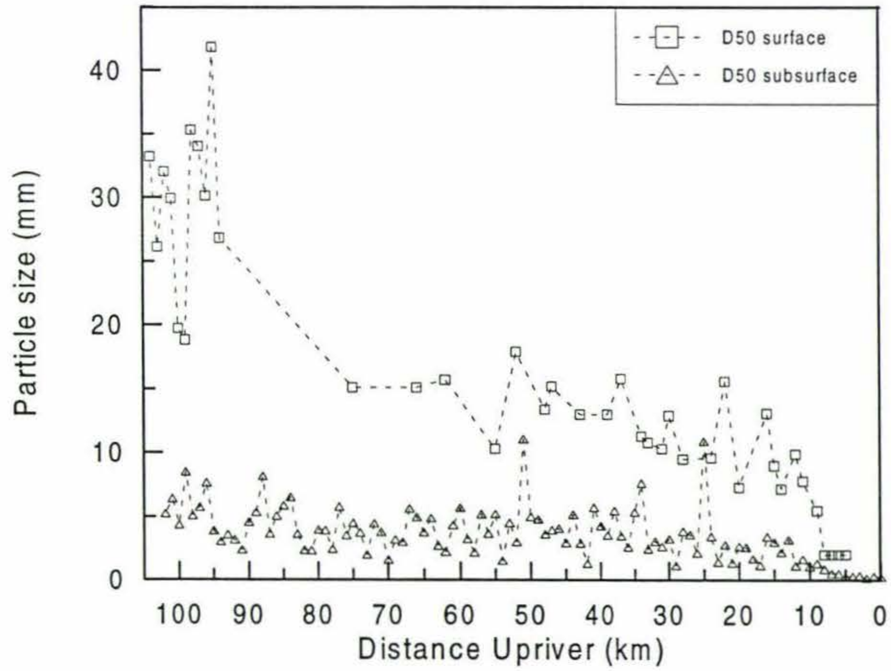


Figure 5.19 Comparison of the median particle size (D_{50}) from the surface and subsurface sediment populations in the Waipaoa River. The surface median particle size exhibited a much greater rate of decrease downstream, as compared to the subsurface median particle size.

material therefore reflected conditions experienced during Cyclone Bola. The surface bed material, however, has been subjected to rearrangement and reorganisation by more frequent, but lower magnitude flood events (or freshes), during which extensive bedload transport did not necessarily occur.

Particle size distributions; The particle size distribution curves varied considerably over the length of the Waipaoa River, but in general the particle size distributions were polymodal. The highest degree of polymodality was exhibited in the upper reaches, above the gorge, so it can be assumed that the presence of three or more particle size subpopulations was a reflection of the sediment supply to the Waipaoa River, rather than a product of fluvial transport. Five common particle size modes or subpopulations consistently appeared in the distribution curves. These subpopulations occurred at approximately 1) 16.21 mm, 2) 5.54 mm, 3) 2.04 mm, 4) 0.59 mm, and at 5) 0.22 mm, although typically only three or four of these subpopulations were present simultaneously. For an example refer to Figure 5.20. The proportion of the particle size distribution curve that was occupied by the various subpopulations changed according to the position in the river. In general, the coarser subpopulations were more prominent in the bed material samples from the upper reaches, and the proportion of the curve occupied by the finer subpopulations became greater downstream. However, the medium sand mode, positioned at ~ 0.22 mm, was present from the headwaters to the coast, and represents the suspended sediment population of the bed material. Average particle size distribution curves for each 10 km reach are presented in Figure 5.21. In general, the particle size distributions became more peaked downstream, although a greater proportion of bimodal grainsize distributions also were encountered in the lower reaches.

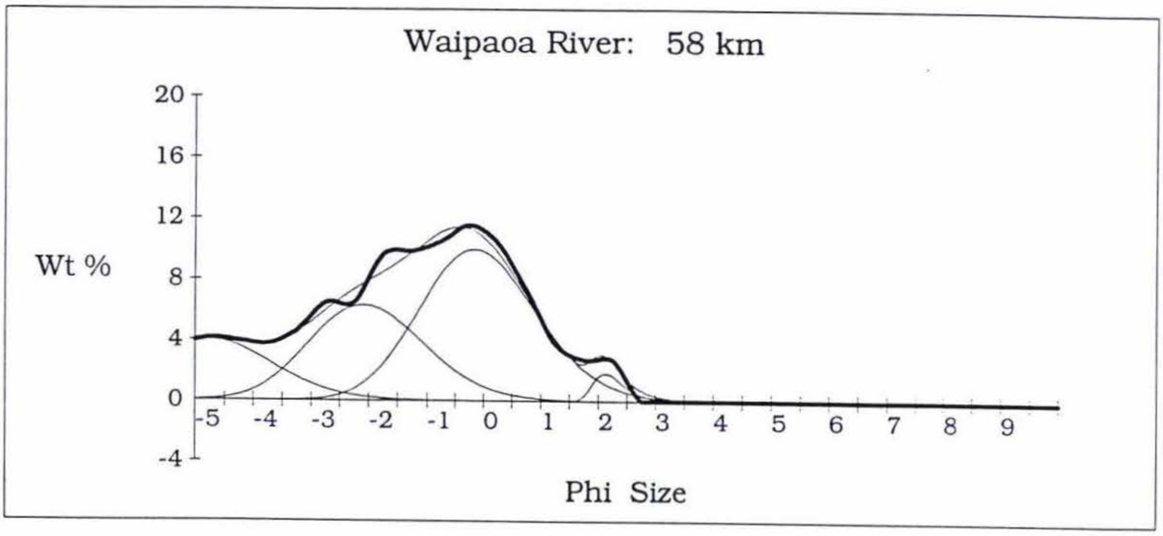


Figure 5.20 A typical particle size distribution of the Waipaoa River subsurface bed material, illustrating the polymodal nature of the sediment, and the commonly exhibited particle size subpopulations.

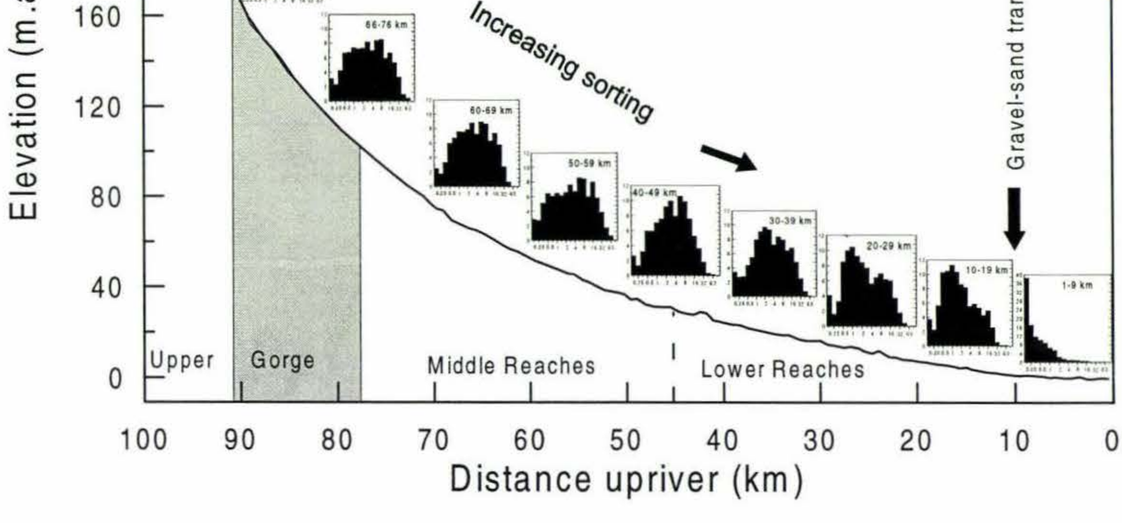


Figure 5.21 The variation in particle size distribution curve along the Waipaoa River, shown in relation to the longitudinal profile of the river. (MBL data from GDC).

The longitudinal variation in the sorting of the particle size distributions are presented in Figure 5.22. Inclusive graphic standard deviation was used as a measure of the sorting of the Waipaoa River subsurface bed material. Inclusive graphic standard deviation was employed because the formula encompasses 90 % of the distribution curve, and it is the best overall measure of sorting (Folk, 1974). Sorting is defined as the process by which particles that possess particular characteristics (such as size, shape or density) are naturally separated from associated, but dissimilar particles (Whiting, 1996). Longitudinal sorting is the segregation of particles in the downstream direction by the action of stream flow, and is manifest in the particle size distribution curve by the concentration of particles within or near a narrow particle size range. Subsurface bed material samples were very poorly sorted in the upper reaches, and the degree of sorting increased slightly downstream. In the reach upstream of the gravel-sand transition, the bed material was poorly sorted, but the sorting had improved from 2.87 Ø to 1.57 Ø over the length of the river. The downstream trend in sorting was significant at the 95 % confidence level ($R^2 = 0.73$). Sorting exhibited the greatest rate of increase with distance in the upper 10-12 km, as well as in the lower 8 km (sand bed reach). Sorting exhibited strong positive correlation coefficients ($R^2 = 0.80$) with distance downstream in both reaches. Downstream from the gravel-sand transition, the sorting improved markedly, and the subsurface bed material samples exhibited very well to well sorted particle size distributions. Sorting exhibited a downstream increase an order of magnitude greater through the very upper (102-91 km) and lower reaches (8-0 km), compared with the remaining river length (91-9 km). The rapidly increasing sorting coefficient in the upper reaches is a reflection of the rapidly declining particle size, due to particle breakdown, as well as the effects of selective transport. The rapid downstream improvement in the sorting coefficient also suggests that selective transport was enhanced in the upper 10-12 km reach, due to the combined effects of aggradation and a rapid sediment supply rate. Brierley and Hickin (1985) suggested that hydraulic sorting may be more efficient under conditions of a rapid sediment supply, that often is encountered near major sediment sources.

Longitudinal trends in the skewness of the particle size distributions are shown in Figure 5.23. Skewness is a measure of the degree of asymmetry of the particle size distribution curve, and the sign of the skewness reflects whether the curve is skewed towards the coarse (negative), or fine (positive) particle size fractions (Folk, 1974). Particle size distribution curves from the upper reaches in the Waipaoa River were negatively skewed (mean skewness 102-98 km = -0.23), and in the lower reaches of the Waipaoa River were positively skewed (mean skewness 8-13 km = 0.126). However, the trend of slightly increasing skewness downstream was not significant at the 95 % confidence level (R^2 = 0.071).

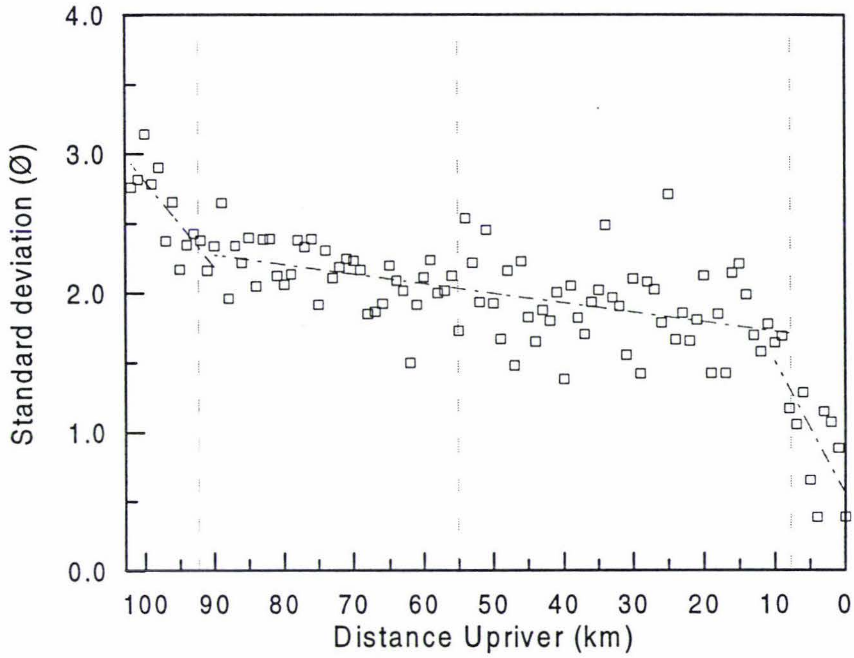


Figure 5.22 Longitudinal variation in the (inclusive graphic) standard deviation of the subsurface bed material samples. The standard deviation was used as a measure of the sorting of the bed material.

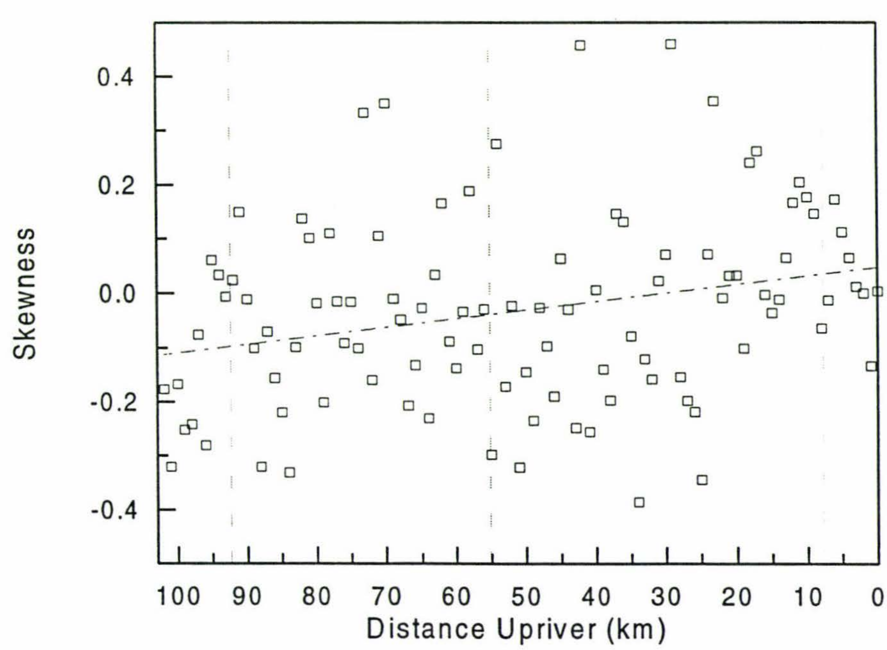


Figure 5.23 Longitudinal variation in the skewness of subsurface bed material samples.

A deductive model was proposed by McLaren (1981) and McLaren and Bowles (1984), which demonstrated the expected changes in particle size distributions in the direction of transport. It was proposed that sequential deposits become either coarser, better sorted, and more negatively skewed in the direction of transport under high energy conditions (such as beach environment), or, sediment deposits become finer, better sorted, and more positively skewed in the direction of transport, in low energy conditions (such as a river). Although the bed material of the Waipaoa River did exhibit significant trends of becoming finer, and better sorted downstream, no significant trend was observed in the skewness data. It is likely that the lack of significant downstream trends in skewness was a reflection of the high proportion of fine material that was observed in the bed material, over the entire length of the Waipaoa River. A fine tail was present in every particle size distribution curve, including those obtained from the upper reaches, and suggests that the particle size distribution curves were dominated by fine particles.

The descriptive parameters of sorting and skewness essentially were devised for describing sediment mixtures that exhibit log-normal particle size distribution curves (Folk, 1974). Subsurface bed material samples from the Waipaoa River are generally polymodal, and therefore do not exhibit log-normal distribution curves. Examining the downstream transformation of the various particle size subpopulations afford an improved understanding of the downstream alteration that occur in the particle size distribution of the bed material. It is proposed that each of the prominent particle size subpopulations observed in the Waipaoa River subsurface bed material corresponded to a different subpopulation that was formed by the successive fragmentation of large particles, and the subsequent modification of the subpopulations by fluvial processes. Sequential fragmentation transport theory (SFT) was developed for the quantitative modelling of particle size distribution curves of sediment populations formed by the sequential fragmentation of 'parent' particles, and the subsequent modification (or sorting) of the population by a liquid or gaseous transport media (Wohletz *et al.*, 1989). Sequential fragmentation is the process by which a single large ('parent') particle is broken up into many smaller particles, of the same total mass as the original particle. It is anticipated that each 'daughter' particle is subsequently broken down into smaller particles, and so on. Wohletz *et al.* (1989) likened the process to a cascading mechanism, that is similar to the processes that particles undergo in a grinding mill. The SFT model originally was developed for use on pyroclastic tephra deposits, but its application is widely suited to a range of clastic deposits (Wohletz *et al.*, 1989).

In the Waipaoa River, particle fragmentation was occasioned by the desiccation of particles while exposed on the river bed. Particles of fine grained rocks supplied predominantly by the Mangatu Formation, specifically siltstone, shale and argillite, when subjected to repeated cycles of wetting and drying, fragment *in situ*. Small piles of typically 8-22 mm angular particles were commonly observed on the bed surface of the Waipaoa River, above the gorge, and its tributaries (Figure 5.24 and 5.25). The piles of angular particles were formed by the fragmentation of a single large particle. The many small particles produced by the fragmentation of a single cobble or boulder can be entrained by flows of lower magnitude but greater frequency than the 'parent' particle. The 'daughter' particles were therefore transported through the river system with greater ease. The SFT model seems particularly applicable to the Waipaoa River. 'Parent' particles underwent initial fragmentation in the upper reaches, and were subsequently subjected to fluvial abrasion and sorting processes on their passage through the river system. Larger particles, such as cobbles and boulders were the most susceptible to desiccation, due to their reduced mobility and the greater likelihood that they will remain *in situ* throughout a series of flood events, allowing the particle to dry out between individual events. The smaller the particles become, the less likely that fracturing by desiccation will occur. This is because greater energy is required to fracture a smaller particle, and smaller particles are less likely to possess planes of weakness (Sharp & Gomez, 1986). By implication, fracturing by desiccation was less likely to occur in the downstream direction, as the particle size of the bed material decreased, and the degree of resistance to desiccation increased. The presence of rounded particles in all particle size fractions in the bed material downstream from the gorge was consistent with the notion that particle breakdown by fragmentation becomes less important in the downstream direction.

Application of the SFT program (Wohletz, 1996) to the Waipaoa River suggests that each of the common particle size subpopulations in the subsurface bed material in the headwater reaches correspond to a 'daughter' population formed by the sequential fragmentation of

Figure 5.24 Tessellated particles from the fragmentation of large siltstone particles on the surface of Te Weraroa Stream (Dec 1996)

Figure 5.25 Siltstone particle on the surface of Te Weraroa Stream in the initial stages of fragmentation by dessication (Dec 1996).

the largest clasts in the bed material. Effectively, this means that the particles comprising the subpopulation situated at approximately 16 mm, underwent fragmentation to produce the finer particle size subpopulation situated at ~ 5 mm. These particles in turn fragmented to produce the 2 mm subpopulation, and then the 0.5 mm subpopulation. These modes were identified by application of the SFT program (Wohletz, 1996) in the upper reaches, as well as in subsequent downstream reaches in the Waipaoa River. By the identification of each of the subpopulations, as well as their corresponding proportion in the particle size distribution curves, the evolution of each subpopulation was traced through the river system.

The modal particle size of each subpopulation, and its corresponding proportion of each grain size distribution at each sampling site are presented in Figure 5.26 and Figure 5.27, respectively. Each of the particle size subpopulations changed slightly in the downstream direction, and all but subpopulation 2 exhibited downstream fining. Subpopulation 2, situated at approximately 5.6 mm, became slightly coarser downstream. The slight downstream fining evident in the particle size subpopulations probably is a reflection of fluvial sorting and abrasion processes. All five particle size subpopulations were present in the headwater reaches, and in subsequent downstream reaches, but the proportion of each subpopulation changed in the downstream direction. The subpopulations centred at approximately 2 mm and 0.5 mm increased in proportion downstream, at the expense of the particle size subpopulations centred at approximately 16 mm and 5 mm. The downstream variation in the proportion of each subpopulation present is not systematic nor statistically significant, however, the trends are evident, and suggests that the finer subpopulations were preferentially transported through the river system, while the coarse subpopulations were selectively deposited. The finer subpopulations therefore were relatively enhanced in downstream bed material samples, and the coarser subpopulations were relatively depleted in downstream bed material samples. Downstream from the gravel-sand transition (~8 km), only subpopulation 5 (at ~0.22 mm) was present.

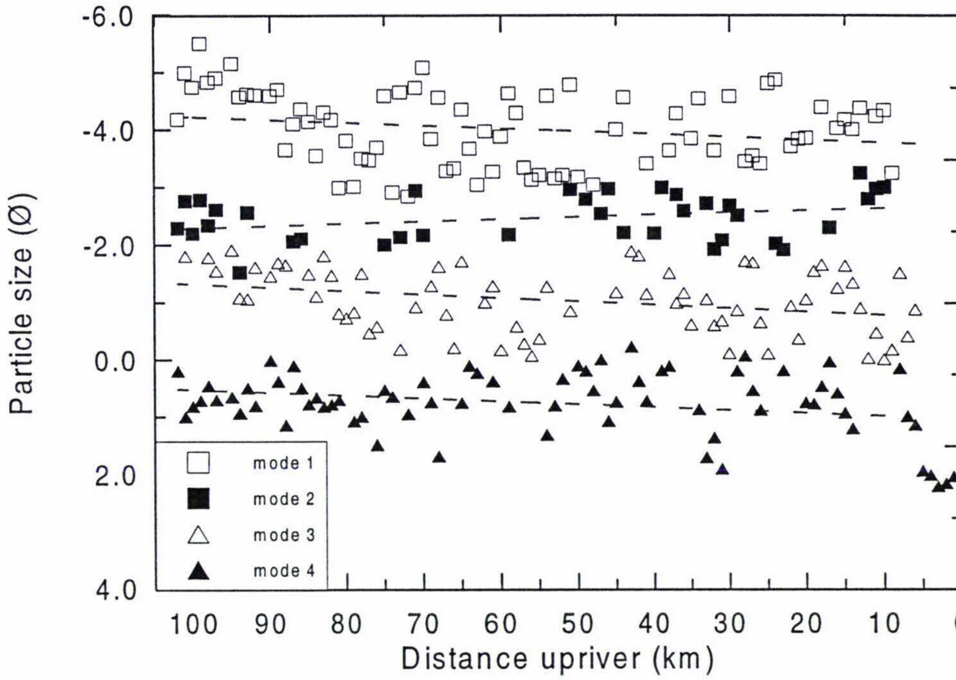


Figure 5.26 The downstream variation in each particle size subpopulation in subsurface bed material samples.

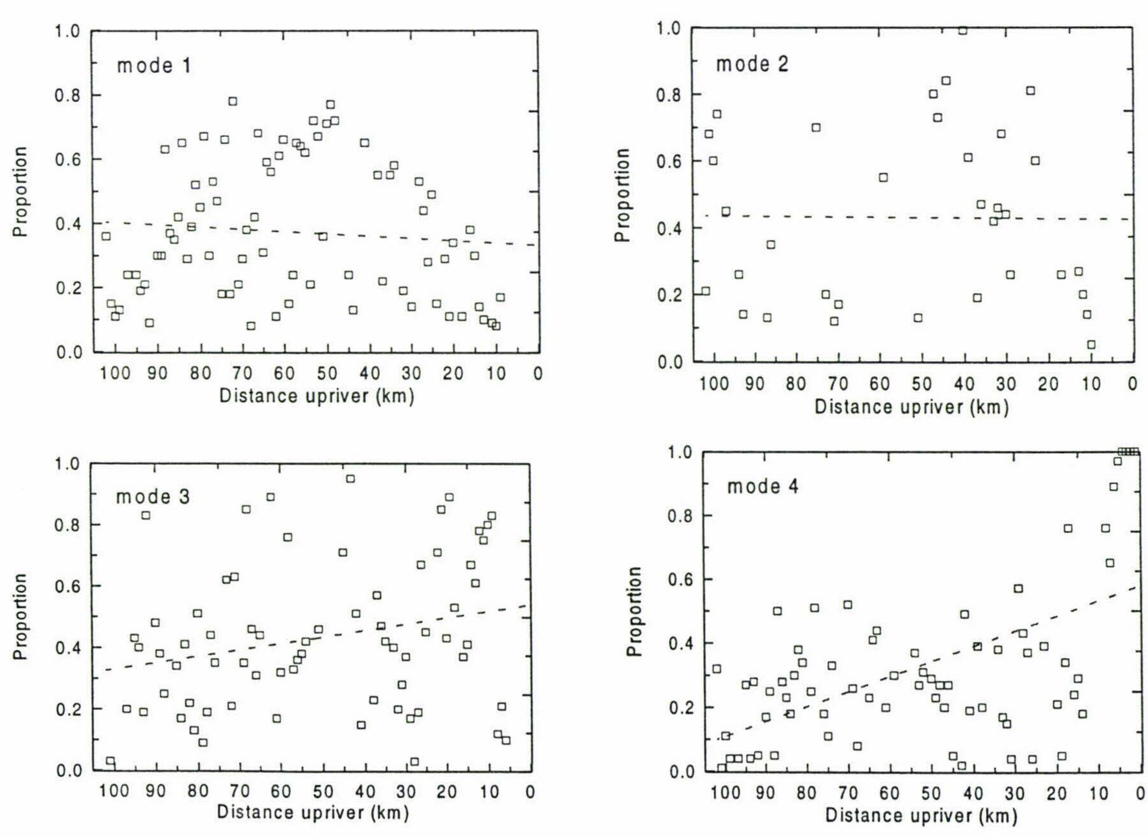


Figure 5.27 The change in proportion of each subpopulation present in the subsurface bed material samples.

The gravel - sand transition; At approximately 8 km from the coast, the Waipaoa River underwent a rapid transition from a gravel-bed to a sand-bed channel. The subsurface bed material D_{90} declined from 13.13 mm to 0.84 mm within a distance of ~2 km, and over the same distance the D_{50} declined from 2.22 mm to 0.36 mm (Figure 5.28). Bed surface samples correspondingly decreased from 18.49 mm to 5.8 mm, and 8.95 mm to < 2 mm for the D_{90} and D_{50}, respectively. Surface D_{90} decreased to sand size by 5 km. However, during Cyclone Bola, in March 1988, gravel sized material was transported through the lower 'sand-bed' reach of the Waipaoa River, and formed an emergent bar at the Waipaoa River mouth (Mazengarb, personal communication 1996). The gravel-sand transition is an important aspect of downstream fining, but, it is often ignored in studies of fluvial sedimentology. The transition from a gravel-bed to a sand-bed channel represents a major change in the behaviour of the river, rather than a simple continuation of downstream fining processes (Sambrook-Smith and Ferguson, 1995).

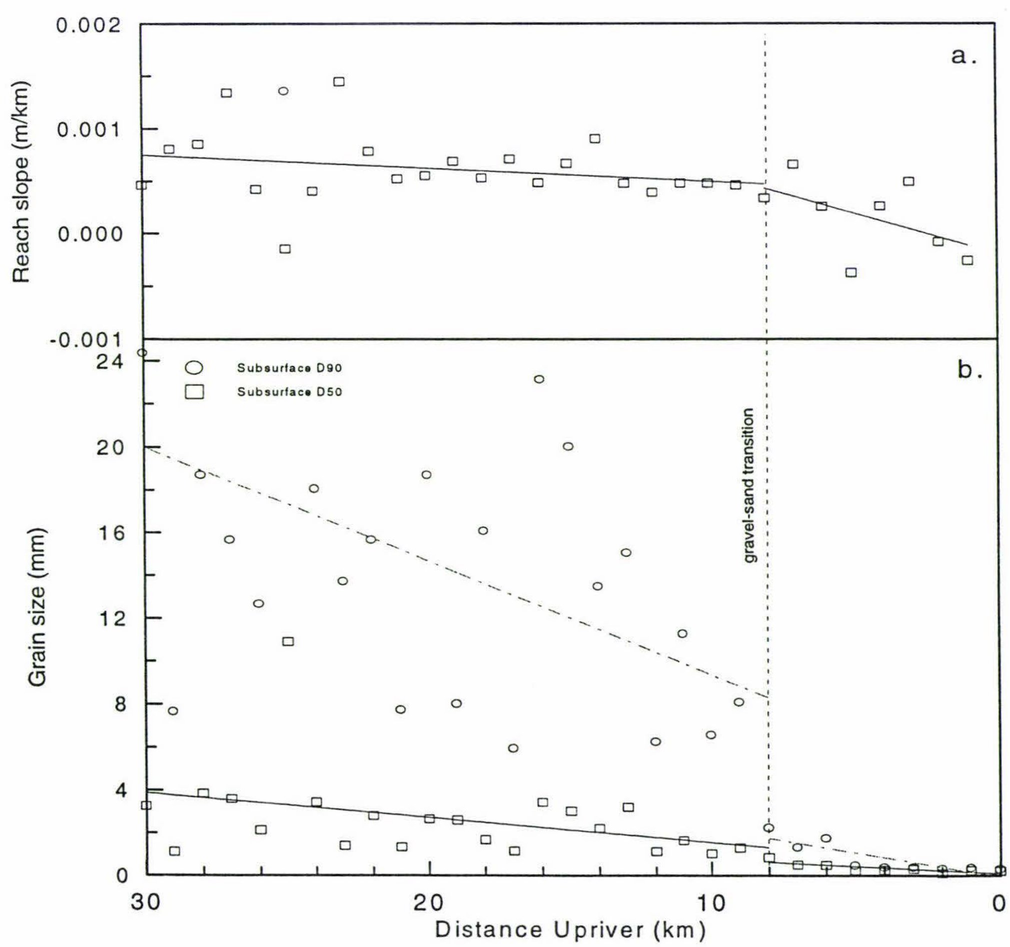


Figure 5.28 Variation of a) slope and b) particle size at the gravel-sand transition, highlighting the abrupt change from a gravel-bed to a sand-bed channel.

The changes in key variables at the gravel-sand transition are summarised in Table 5.3. Bed slope was very low through the transition reach, typically 0.0006 m km^{-1}, and declined to 0.0002 m km^{-1} after the transition. The bed material generally was polymodal over the length of the Waipaoa River, but became weakly bi-modal a short distance (4 km) upstream of the gravel-sand transition. Downstream from the transition, the grain size distribution of the bed material was unimodal, with a peak in the medium to fine sand range. Figure 5.30 illustrates the transformation of the bed material particle size distribution above and below the gravel-sand transition.

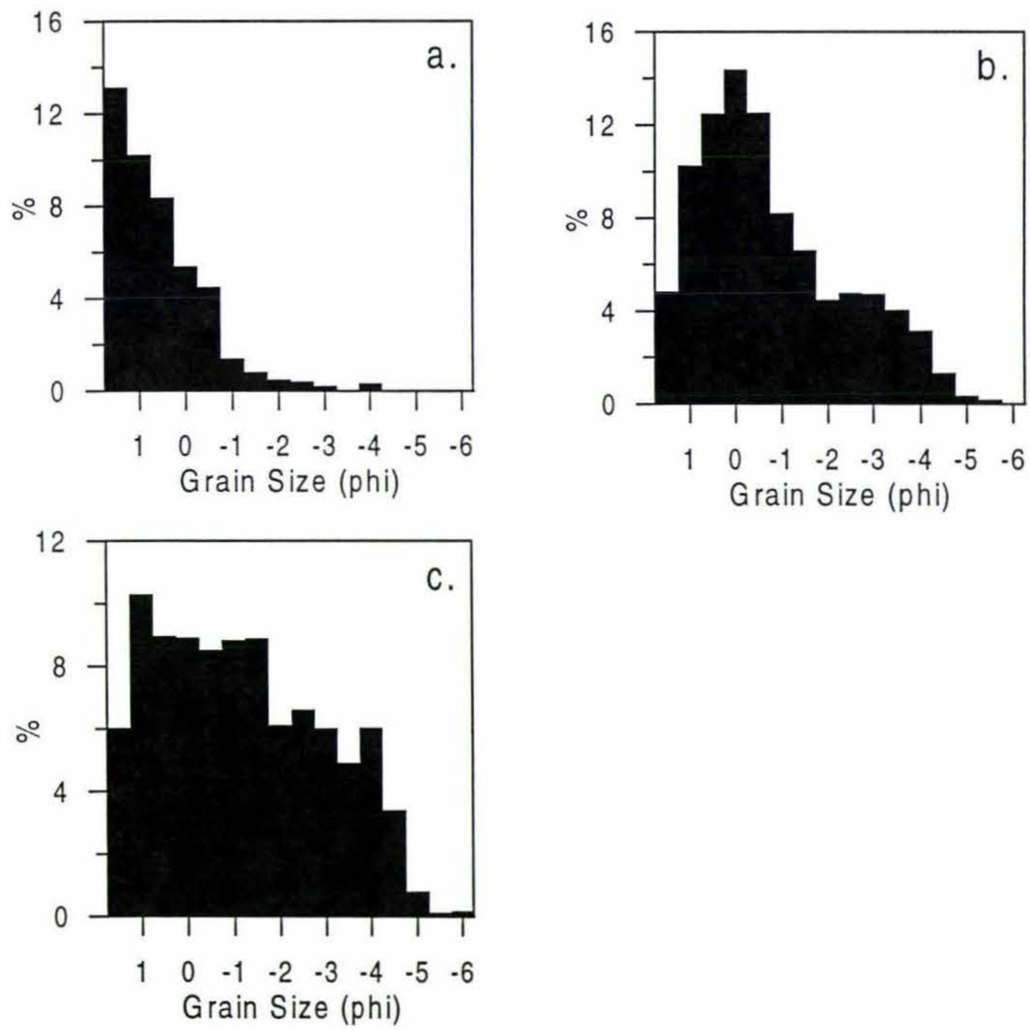


Figure 5.30 Subsurface particle size distributions from a) downstream from the gravel-sand transition, b) 0-5 km upstream of the gravel-sand transition, and c) >5 km upstream of the gravel-sand transition in the Waipaoa River

Table 5.3 Variation in key morphological variables before and after the gravel-sand transition in the Waipaoa River.

Variable			gravel reach	sand reach
Grain size (mm)				
	subsurface	D90	13.13	0.84
		D50	2.22	0.36
		% sand	30-40	100
		modality	bimodal	unimodal
	surface	D90	18.49	5.8[1]
		D50	8.95	< 2
Bed slope (m/km)		reach[3]	0.00061	0.00016
Width (m)[3]			58	100-400[2]
Depth (m)[3]			9.5	4.3

[1] Surface D90 decreases to < 2 mm 5 km from the river mouth.
[2] Channel width increases from 58 to 113 m between 8 and 10 km, below 8 km width steadily increases from 113 to 420 m at river mouth.
[3] Data source: Gisborne District Council

In the Waipaoa River, a reduction in bed slope occured due to local base level control by the sea. A reduction in bed slope without a corresponding decrease in sediment supply is expected to induce aggradation (Sambrook Smith & Ferguson, 1996). Aggradation was not encountered in the lower 25 km reach, so a decrease in sediment supply (and size) probably occurred by the selective deposition of coarsest size fractions of the bed load. The result is that the bedload becomes progressively finer, and the material supplied to the downstream reaches also becomes progressively finer (Sambrook-Smith, 1996).

The tidal limit in the Waipaoa River was situated approximately 10.5 km upriver from the river mouth (Peacock, personal communication 1996). The cross sectional area of the channel increased dramatically downstream of this point (refer to Figure 5.42), and the transition from a gravel-bed to a sand-bed channel occurred a short distance downstream. Average channel width abruptly increased from a fairly constant 60 m, to ~100 m between 10 and 8 km. The channel width consistently increased from this point to ~400 m at the river mouth. Channel depth correspondingly decreased from 9.5 m to 4.3 m, over the same distance. The channel therefore was becoming wider and shallower, but the increase in width was much greater than the decrease in depth, and channel cross-section area therefore increased. The cross sectional area increased in response to the increased quantity of water that must be contained within the channel banks at high tide.

An increase in hydraulic radius causes a decrease in the boundary shear stress, so that progressively finer particles are deposited on the bed (Whiting, 1996). It seems likely that the transition from a gravel-bed to a sand-bed channel in the Waipaoa River was related to the increase in cross sectional area associated with the tidal limit. A channels response to spatial variation in boundary shear stress, in this case induced by increasing hydraulic radius, can be achieved almost entirely through bed grain size adjustment by selective deposition, without requiring a break in slope (Whiting, 1996). A similar conclusion was drawn by Paola *et al.* (1992) when modelling downstream fining in a laboratory flume. Shaw and Kellerhals (1982) proposed a mechanism for producing gravel-sand transitions in Albertan Rivers by the crushing of 8-16 mm gravel during fluvial transport. This mechanism does not require a break in slope either. In the Waipaoa River, the median grainsize always was within this particle size range, so the crushing of 8-16 mm grains cannot explain the rapid decrease in grainsize within a 2 km reach.

Sediment data from the Waipaoa River suggest that the transition from gravel to sand texture occurred earlier in the subsurface, than for surface sediment populations. Coarser particles have formed a lag on the surface downstream of the gravel-sand transition in the Waipaoa River. This coarse material was present on the surface only, and may have been supplied to the channel by bank erosion between 6 and 10 km, where lenses of fine gravels were occasionally present within the fine grained floodplain deposits of the banks. Additionally, a small amount of gravel overpassing may have occurred over the fine bed for a nominal distance downstream of the gravel-sand transition. Coarse particles on a fine bed experience enhanced mobility, because the geometry of the bed surface does not provide suitable sites for the trapping and deposition of larger particles (Whiting, 1996).

The introduction of saline water and bi-directional flow associated with the tidal limit in the Waipaoa River probably had the effect of enhancing the abruptness of the gravel-sand transition. Salinity causes some clay minerals to flocculate, and encourages their deposition (van Leussen, 1988). This represents a mechanism for the deposition of fine material during low flow conditions that otherwise would remain in suspension. The introduction of bi-directional flow complicates matters also. During low to moderate flow, the incoming tide impedes sediment motion, possibly even causing fine material to be transported upstream. This process was observed on several occasions in 1996, while bed material sampling. The Waipaoa River carries a very high suspended sediment load, so an endless supply of fine sediment was available for deposition.

What happens to the gravel that is constantly moving down the river? Analysis of cross sectional data over the last 50 years strongly suggest that the reach below 20 km was degrading, so gravel was not building up in this reach. Several factors have lead to the suggestion that the gravel-sand transition in the Waipaoa River was a spatially and temporally variable phenomena. Bed material samples obtained by the Gisborne District Council from the lower reaches of the Waipaoa River in October 1988 indicated that the bed material was considerably coarser at that time. Gravel sized material was transported through the lower 'sand-bed' reaches of the Waipaoa River during Cyclone Bola, and formed an emergent bar at the river mouth (Mazengarb, personal communication 1996). The particle size distributions obtained from the lower reaches in 1988 and 1996 are compared in Figure 5.30. At the 5 km sampling location, the D_{90} was 10.9 mm in 1988, compared to 0.8 mm in 1996, and the D_{50} was ~1.9 mm in 1988, compared to ~0.2 mm in 1996. Similar magnitude differences were observed between 1988 and 1996 bed material samples from the 11 km sampling location. Historical evidence also suggests that the gravel-sand transition in the Waipaoa River was a temporary phenomena. During the 1940's, the county gravel pit was located in the Waipaoa River channel just downstream of Matawhero (~9 km) (Dennis, c1949). The pit was observed to fill with gravel sized material after each flood event, and demonstrated that gravel was transported through this reach of the Waipaoa River at high flow (Dennis, c1949).

The existence of the gravel-sand transition in the Waipaoa river appears to be related to the timing of large magnitude flood events. During periods in which no large floods occur (*ie.* 1988 to 1996), gravel sized material is deposited on the river bed in the reaches above 8 km, possibly causing slight aggradation, and a sand bed channel is developed downstream from this point. During extreme, large magnitude events, such as Cyclone Bola, the large increase in bed velocity probably outweighed the increase in hydraulic radius, and a considerable quantity of gravel was moved through the lower sand-bed reaches, to be deposited in Poverty Bay.

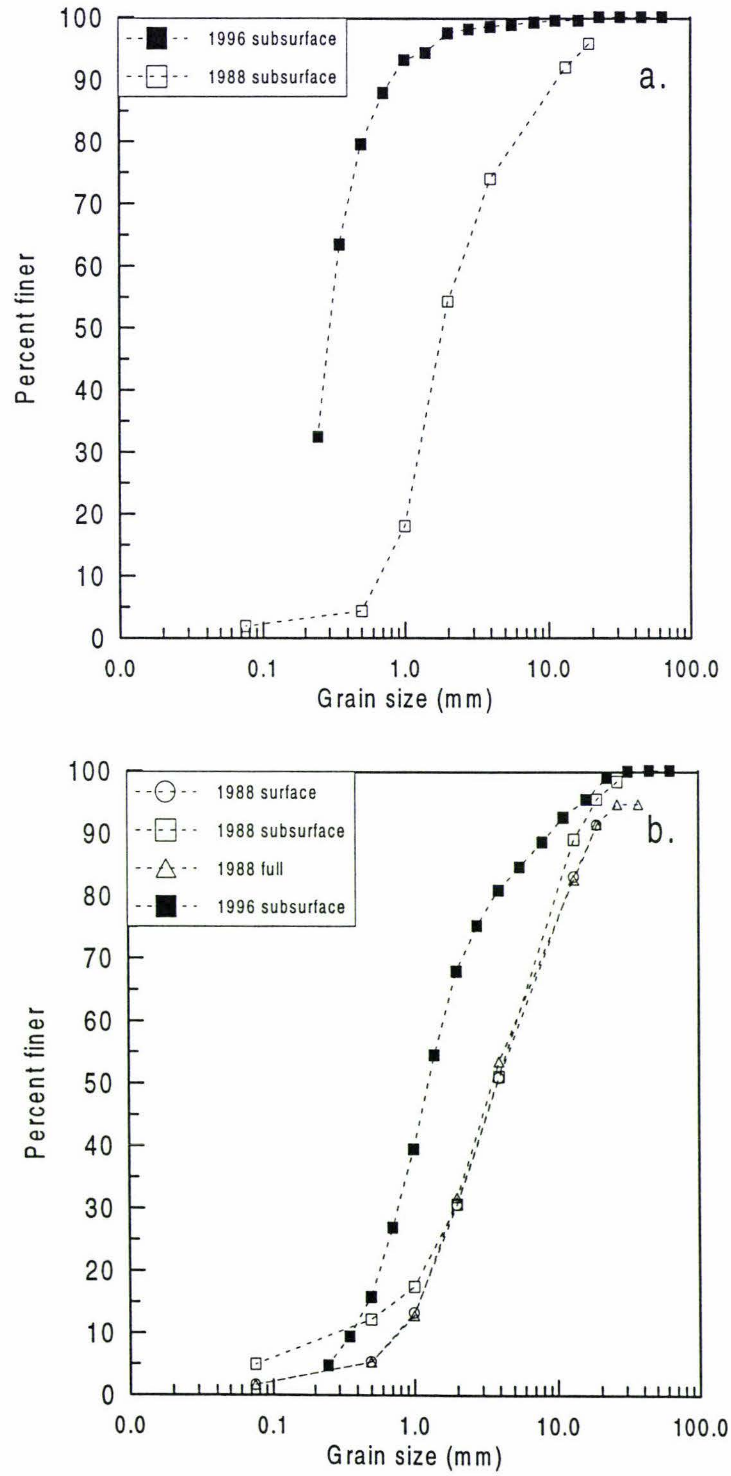


Figure 5.30 Particle size distribution curves for the sand-bed reach in 1988 and 1996, at a) 5 km and b) 11 km, illustrating the temporal variation in particle size.

Downstream fining; Fining coefficients for each of the calculated particle size fractions (D_5 to D_{95}) are presented in Table 5.4 The fining coefficients were calculated by the method outlined by Shaw and Kellerhals (1982), over the gravel-bed portion of the Waipaoa River (102-8 km). The equation used to calculate the fining coefficients implies that selective transport and fluvial abrasion followed an exponential decline in the downstream direction (Shaw & Kellerhals, 1982).

Downstream fining in the Waipaoa River was concentrated in the coarser particle size fractions of the subsurface bed material, and all particle size fractions above the median (D_{50}) exhibited similar fining coefficients (~0.013). Particle size fractions below the median grain size experienced a rate of fining an order of magnitude lower than those above the median. Particle size fractions coarser than the median exhibited enhanced downstream fining because of the action of selective transport of the finer particle size fractions. This is consistent with the notion that the coarsest particle size fractions of the bed material represent the limiting condition of stream competence (Wilcock, 1967; Brierley & Hickin, 1985).

Table 5.4 Fining coefficients for each particle size fraction, calculated over the gravel-bed portion of the Waipaoa River.

	Fining Coefficient	
Size	Subsurface	Surface
D_{95}	0.0113	0.0140
D_{90}	0.0123	0.0138
D_{84}	0.0131	0.0135
D_{75}	0.0133	0.0135
D_{65}	0.0131	0.0135
D_{50}	0.0087	0.0138
D_{35}	0.0056	0.0147
D_{25}	0.0033	0.0149
D_{16}	0.0033	0.0156
D_5	-0.0007	0.0146

Similar relationships between particle size fractions and the rate of downstream fining were observed by Paola *et al.* (1992) in a laboratory flume. The higher percentiles, representing the coarse tail of the particle size distribution, exhibited the greatest rate of downstream fining. Downstream fining in the laboratory flume was produced by the selective deposition of the coarsest size fractions of the bed load (Paola *et al.*,1992). The faster rate of downstream fining also was concentrated in the coarser size fractions of the Waipaoa River bed material because these particle sizes (coarse gravel and cobbles) were more likely to be affected by physical weathering processes, such as desiccation and fragmentation, while exposed on the river bed.

Particle size fractions of the surface bed material exhibited a rate of downstream fining comparable to the subsurface bed material, but the highest fining coefficients were obtained for the finer size fractions (D_{16} to D_{35}). The finer particle size fractions of the surface bed material more closely reflected the particle size of the coarser fractions of the substrate bed material, which also exhibited the highest rate of downstream fining. The faster rate of downstream fining obtained for the finer fractions of the surface bed material also can be attributed to the enhanced mobility of the fine fractions, relative to the coarser size fractions, as well as the greater probability of entrainment. The characteristic particle size fractions of the surface bed material are expected to exhibit a greater rate of downstream fining than the subsurface bed material as a result of the greater frequency of entrainment or re-arrangement by the flow.

Fining coefficients were obtained for different reaches of the Waipaoa River that exhibited a distinct channel morphology, and also were calculated by the method used by Shaw and Kellerhals (1982). The fining coefficients are presented in Table 5.5. Downstream fining either can be considered as the result of sorting and abrasion processes that operate in a manner that is spatially continuous and independent of channel planform pattern, or the reaches that exhibited distinct channel morphologies behave as distinct sedimentation environments, that manifest their own characteristic rates of downstream fining (Brierley & Hickin, 1985). In the latter case, the different morphological reaches are expected to exhibit significantly different fining coefficients.

Table 5.5 Fining coefficients obtained for the D_{50} and D_{90} particle size fractions for different reaches in the Waipaoa River.

Reach		Fining Coefficient	
km	Description	D50	D90
102-8	gravel-bed	0.0086	0.0122
102-91	braided	0.0770	0.0520
91-77	gorge	0.0193	0.0133
77-38	middle	-0.0026	0.0119
38-8	FCS[1]	0.0350	0.0119
91-60	transitional	0.0065	0.0132
60-25	meandering	0.0067	0.0115
25-8	degrading	0.0530	0.0505

[1] Flood Control Scheme

In the Waipaoa River, significantly different fining coefficients were obtained from the reaches that exhibited distinct channel morphologies. This suggests that separate combinations of processes lead to downstream fining in each of the separate reaches. The fastest rate of downstream fining for both D_{50} and D_{90} particle size fractions was observed in the braided upper reaches, above the gorge (102-91 km). The rate of downstream fining generally decreased downstream, although, the rate of downstream fining increased in the lower 25 km reach of the Waipaoa River, for both the D_{50} and D_{90} particle size fractions.

Brierly and Hickin (1985) observed a similar downstream decline in the fining coefficient in the Squamish River, British Columbia, and suggested that a negative power function would better describe the downstream gradation of particle sizes. The faster rate of downstream fining observed in the upper reaches of some gravel-bed rivers suggests that Sternberg's law, in which a constant rate of downstream particle size decline is assumed, may not apply to those reaches of gravel-bed rivers in close proximity to major sediment sources (Brierly & Hickin, 1985). Analogous observations were reported by Bradley (1970) in the Colorado River, Texas, as well as by Adams (1979) in the headwater streams draining the Southern Alps, New Zealand. The rapid breakdown of unsound particles, and selective sorting were considered to be the primary mechanism of downstream fining in these situations.

The faster rate of downstream fining in the reaches above the gorge suggest that downstream particle size decline in the Waipaoa River also would be better described by a negative power function, rather than by an exponential function. A more rapid rate of downstream fining was expected in the upper braided reaches of the Waipaoa River because the highest rate of aggradation also was experienced in this reach. Shaw and Kellerhals (1982) observed that the rate of downstream fining was more rapid in Albertan Rivers that exhibited aggradation. During aggradation the surface bed material is transferred to the substrate as the bed aggrades, as well as in the downstream direction (Toro-Escobar *et al.*, 1996). This process effectively enhanced selective transport, and decreased the mobility of coarse particles in the bed material, and is reflected by the greater increase of the sorting coefficient in the reach above the gorge (refer to Figure 5.22). Enhanced downstream fining also was expected in the upper reaches of the Waipaoa River by the rapid breakdown of unsound particles supplied to the channel from gully erosion, comparable to the South Island rivers studied by Adams (1979). The occurrence of particle fragmentation by desiccation processes also enhanced the rate of downstream fining in this reach. Larger particles, typically cobbles and boulders, were exposed at the surface for extended periods of time (due to their relative immobility), during which time repeated cycles of wetting and drying were experienced, during flood flow, or due to channel switching. Fragmentation by desiccation caused the rapid breakdown of large particles *in situ*, without the necessitation of fluvial transport.

The relatively faster rate of downstream fining documented in the lower reach (25-8 km) was explained by the occurrence of degradation. As outlined previously, the reach from 25 km to the sea has been degrading since the 1950's, with the construction of the Flood Control Scheme. The channel in this reach was shortened by a total length of 8 km by the removal of several large meander bends. As a consequence, the gradient of the river through this reach was steepened, which promoted degradation (Hosking, 1985). The primary cause of downstream fining in degrading rivers is fluvial abrasion (Shaw & Kellerhals, 1982). The relatively greater rate of fining in the lower 25 km reach is attributed to the occurrence of fluvial abrasion, plus selective transport, in this reach. In the Waipaoa River, the occurrence of abrasion enhanced downstream fining in this reach of because the relatively unresistant nature of the lithologies comprising the bed material. It will be shown subsequently that fluvial abrasion has a negligible effect on downstream fining for the remaining length of the Waipaoa River.

The rate of fining was significantly different between the gorge (91-77 km), and the meandering reach (60-25 km), and the gorge reach exhibited downstream fining an order of magnitude greater than the meandering reach. Greater rates of downstream fining are expected in the upper reaches of gravel-bed rivers (gorge) because of the proximity to the sediment source, and the greater effect of selective transport, and in the Waipaoa River, particle fragmentation by desiccation. The effects of selective transport and abrasion are presumed to decrease exponentially downstream (Shaw & Kellerhals, 1982). A higher rate of downstream fining therefore was expected in the upper reaches, as a natural consequence of this.

No significant difference in the rate of downstream fining for the D_{90} was found between the gorge reach (91-77 km), and the middle reaches below (77-38 km). However, the D_{50} exhibited slight downstream coarsening in the reach from 77-38 km, but the trend was not significant at the 95 % confidence level ($R^2 = 1.5 \times 10^{-4}$). No difference in the rate of fining was observed between the meandering reach (8-60 km), and the transitional reach from 60-91 km, for both the D_{50} and the D_{90}.

Additional particle size data were obtained from the surface of the Te Weraroa Stream (Banbury, personal communication 1996), the major stream that contributes sediment to the upper reaches of the Waipaoa River. The longitudinal variation in particle size statistics along the Te Weraroa Stream are shown in Figure 5.31. Particle size data were obtained according to the method proposed by Wolman (1954). Fining coefficients of 0.099 km^{-1} and 0.046 km^{-1} were obtained for the D_{90} and D_{50}, respectively. These fining coefficients were an order of magnitude greater than the fining coefficients obtained in the upper reaches of the Waipaoa River, reflecting the greater proximity of the stream to the Tarndale Gully sediment source, as well as the rapid breakdown of particles by desiccation and fragmentation processes.

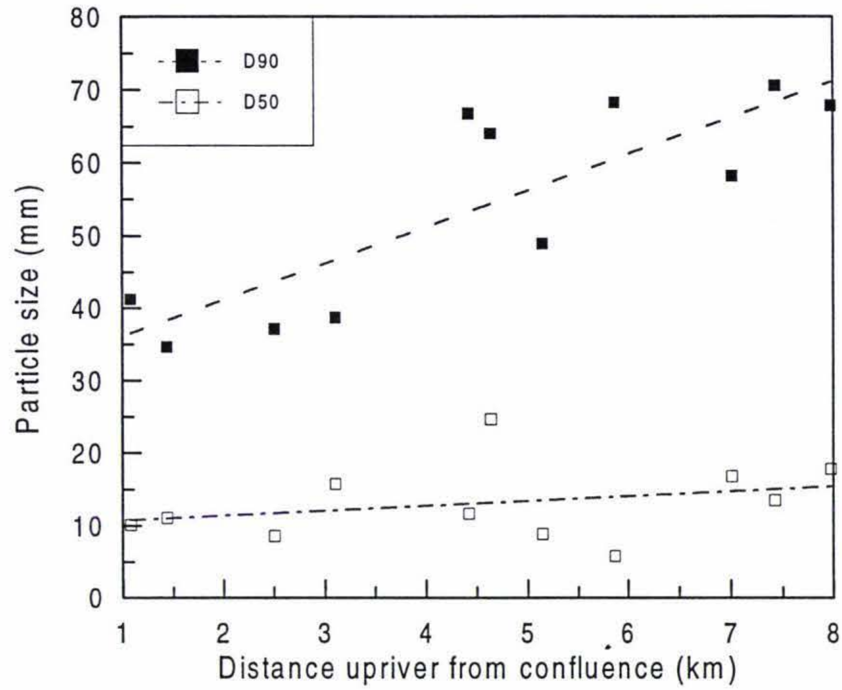


Figure 5.31 Downstream fining in the surface particle size in the Te Weraroa Stream. (Data source: Banbury, personal communication 1996).

5.4 Temporal Variation in Bed Material Size

The particle size statistics for the 1950 to 1960 surveys, conducted by the Poverty Bay Catchment Board, are presented in Figure 5.32. The particle size statistics were comparable to the particle size data obtained in 1996. However, it must be emphasised that the sampling technique employed to obtain the samples is unknown, so it is unclear whether this data can be directly compared to the 1996 particle size data. The particle size data collected in 1950, 1956, and 1960 were very similar to the data obtained by the present study, however, the main deviations from the 1996 data warrant explanation.

The major deviation from the present survey data was between the 1950 and 1956 surveys, for both D_{50} and D_{90}. There was an apparent fining between ~50 and 30 km, where it appears that the bed was composed of predominantly sand and silt. Historical accounts have reported that the Waipaoa River channel between Kaiteratahi (~ 34 km), and Te Karaka (~ 50 km) was covered with silt from 1912 to approximately 1949 (Denis, c1949). The abundance of silt on the river bed was attributed to the extensive growth of willows

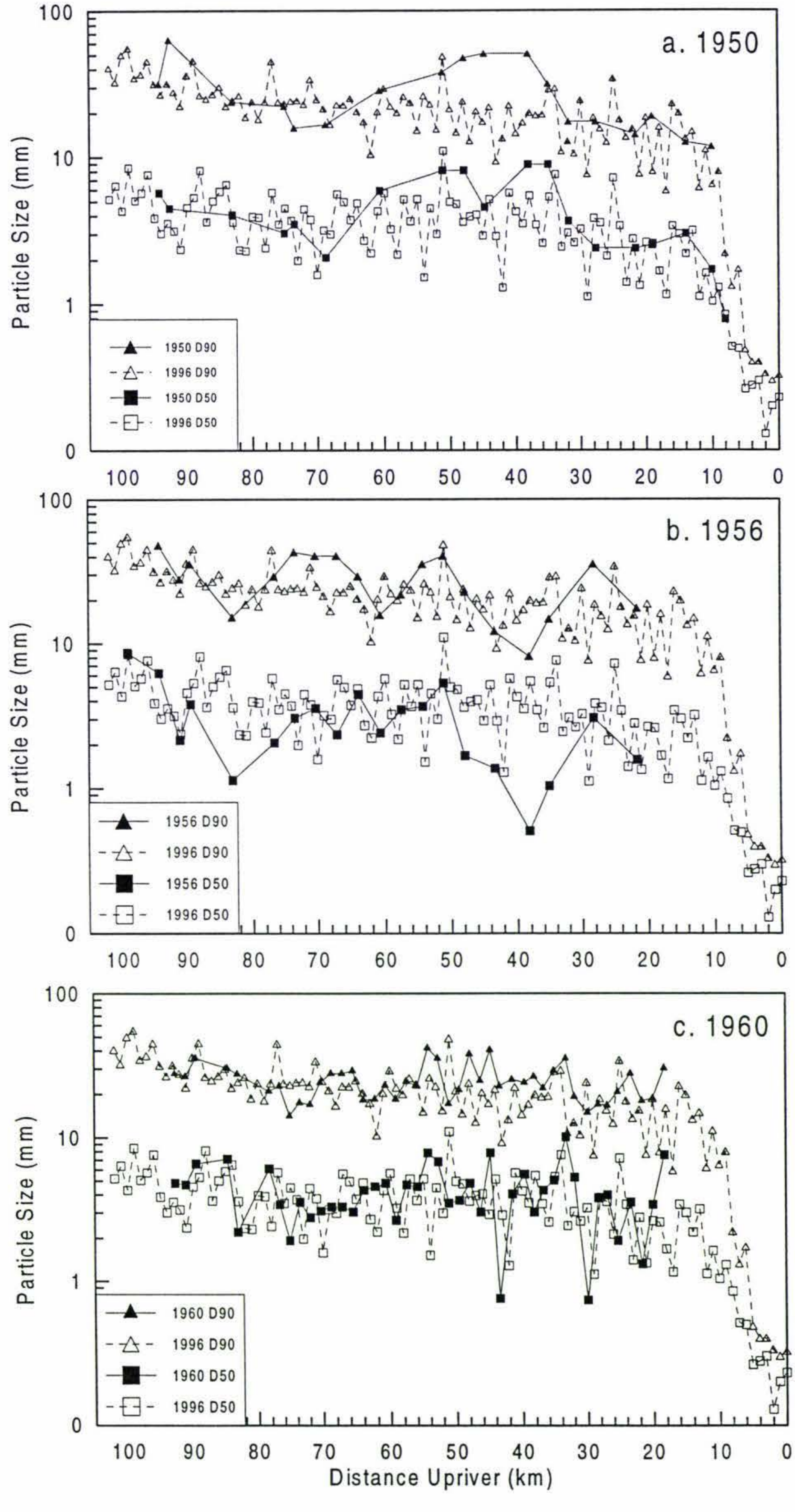


Figure 5.34 Longitudinal variation in the D_{50} and D_{90} for bed material samples collected in a)1950, b)1956, and c)1960 (Data source: GDC). Data are shown in relation to the 1996 particle size data.

that lined the banks and obstructed flood waters. Alternatively, the method of bed material sampling in 1956 may have lead to the collection of bed material samples that were not representative of the material in the channel, and the apparently finer bed material samples were due to sampling error.

The reach between ~ 66 km and 77 km of the Waipaoa River (near Whatatutu), in 1956 (D_{90}) was considerably coarser than the 1996 survey, and both the 1950 and 1960 (D_{50} and D_{90}) surveys were finer than the 1996 survey. This reach was immediately downstream of the confluence with the Mangatu River. Temporal variation of particle size statistics in this reach may have been influenced by erosion/storm activity within the Mangatu catchment. There are accounts of several major floods in the Waipaoa River within this time period (refer to Cowie, 1957).

The reach from ~58 km to 38 km in 1950, as well as in 1960, exhibited individual data points that were considerably coarser than the 1996 survey data (D_{50} and D_{90}). Only one such coarse site was encountered in 1996, at 51 km (refer to Figure 5.6). Inspection of the site at 51 km revealed bank erosion of a coarse terrace deposit, that consisted of particles that were considerably coarser than the material currently moving through the river system. The coarse gravel deposit was underlying a low terrace adjacent to the river. A vegetated mid channel island was formed at the same level as the coarse gravel layer, suggesting that the river could not erode through that part of the bank. The point bar surface immediately downstream of the island and terrace gravel outcrop was composed of cobbles and coarse gravel, and was noted to be strikingly coarser than any other site previously sampled. The greater areal distribution of such coarse samples in the surveys conducted from 1950 to 1960 suggest that the coarse gravel layer may have a greater areal extent than suggested by the 1996 data, and that bank erosion previously has been more extensive through this reach than is currently observed.

Comparison of the survey data collected from 1950 to 1960 by the Poverty Bay Catchment board, reveal that there were no obvious, systematic trends of changing grainsize through time. The overall pattern of downstream fining the Waipaoa River appears to have been well established by 1950, in excess of 50 years after initial changes to the river channel were reported. The observed trends through time, or lack thereof, suggest that the overall pattern of downstream fining was well established prior to the first major survey that was undertaken in 1950, and that the pattern has been maintained as the river system has aggraded. The lack of particle size trends through time also suggest that the particle size statistics obtained in the present survey give an accurate account of the material currently moving through the river system, and substantiate conclusions drawn from the analysis of this data. Good correlation also was found between the 1993, 1994 and 1996 survey data (refer to Figures 4.1, 4.2, and 4.3).

Identical particle size distributions were obtained from the Te Weraroa Stream in 1950 and 1996 (Figure 5.33), further underpinning the notion that the calibre of the bed material in the Waipaoa River, as well as its main tributaries has not changed appreciably during the past 50 years.

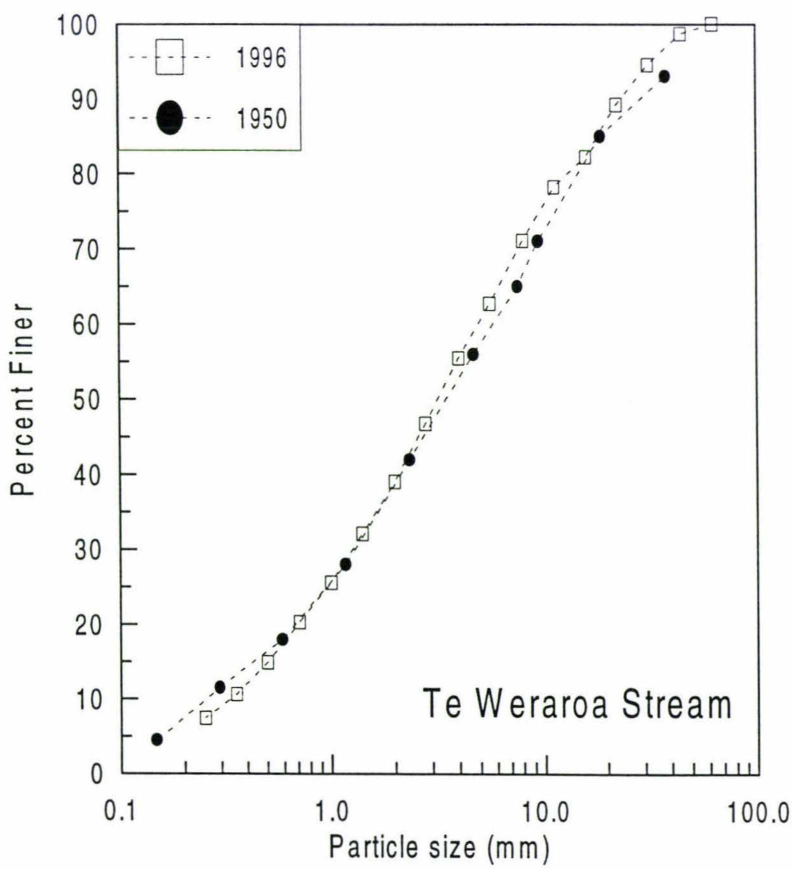


Figure 5.33 Particle size distribution curves obtained from the Te Weraroa Stream in 1950 and 1996 (Data source, 1950 samples: GDC)

5.5 PARTICLE SIZE AND MORPHOLOGIC VARIABLES

The longitudinal profile of the Waipaoa River is concave, and reflects the decline in bed slope downstream. Reach slope, calculated over successive distances of approximately 2-3 km along the Waipaoa River channel, declined from 0.011 m km^{-1} in the headwater reaches to 0.0002 m km^{-1} at the river mouth. Local bed slope, measured over 100 m distances along the bar surfaces at each sampling site, correspondingly decreased downstream from 0.007 m km^{-1} in the headwater reaches, to 0.0003 m km^{-1} at the river mouth. Downstream from approximately 6 km, the mean bed level of the Waipaoa River was below mean sea level.

Longitudinal Profile; The longitudinal profile of the Waipaoa River, shown in relation to the underlying catchment geology at each sampling site, is presented in Figure 5.34. The Waipaoa River is an aggradational river system, consequently, bedrock control on bed slope was absent. Aggradation rates of the order of 5-10 cm yr^{-1} have been observed even through the gorge in the period 1948 to 1960, as well as for the most recent period of 1986 to 1996 (GDC data). Bed rock control was therefore absent through the gorge reach also.

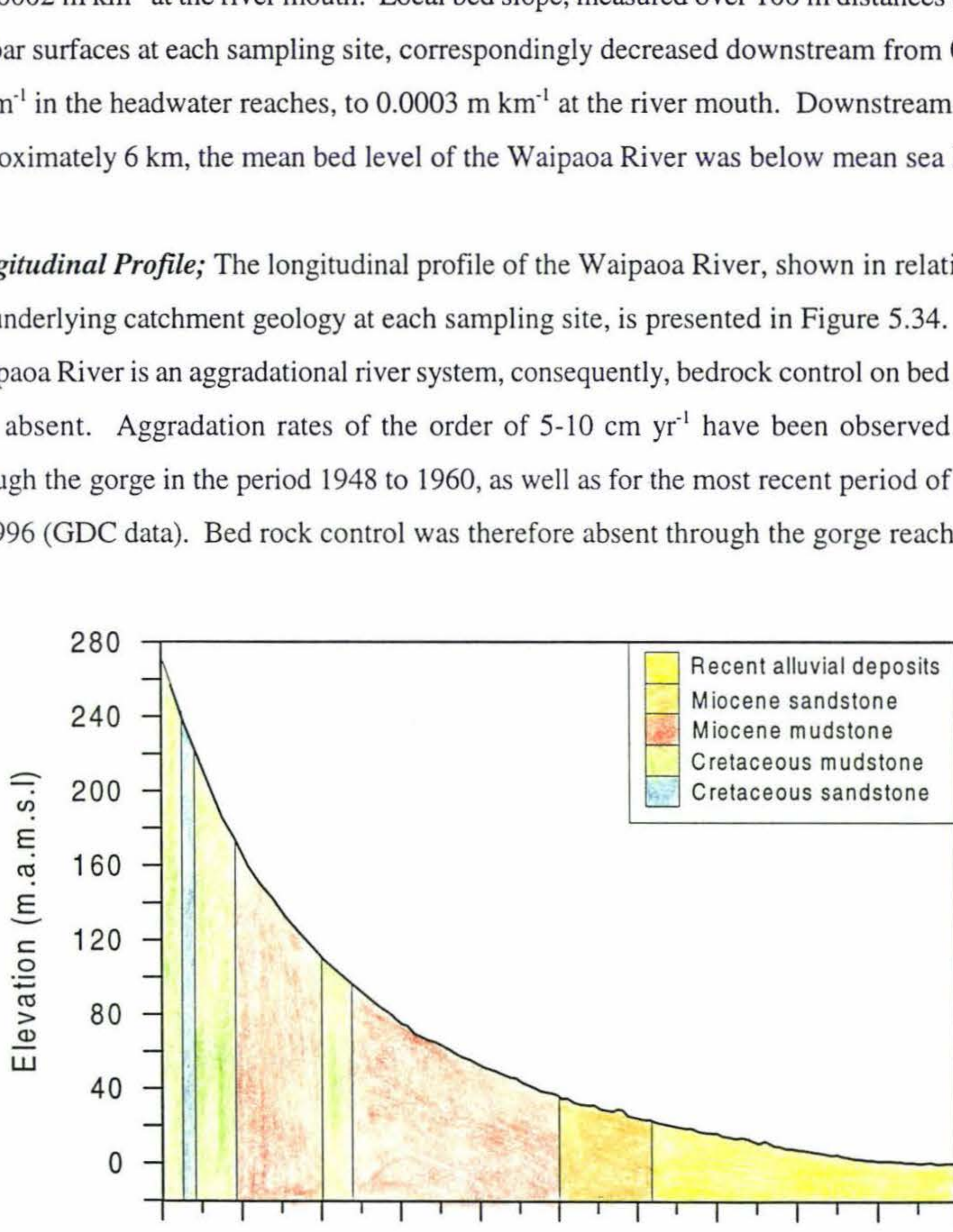


Figure 5.34 The longitudinal profile of the Waipaoa River, illustrating the underlying catchment geology at each sampling site (Data source, MBL data: GDC)

The longitudinal profile of a river traditionally has been described by an exponential curve (Yatsu, 1955). Yatsu (1955) concluded that some Japanese rivers were described by two separate exponential curves, with a break between them coinciding with the location at which the river underwent a transition from a gravel-bed to a sand-bed channel. The longitudinal profile of the Waipaoa River also was described by two mathematical functions; the upper 77 km (102-25 km) was described by an exponential function, and the lower 25 km reach was described by a power function, as shown in Figure 5.35. From 102-25 km in the Waipaoa River, the best fit to the longitudinal profile was achieved by employing the exponential function

$$\log H = 0.0399*X - 1.519 \quad (5.1)$$

(R^2 = 0.998), and the lower 25 km reach was best described by employing the power function

$$\log H = 2.527*\log X - 5.581 \quad (5.2)$$

(R^2 = 0.963), where H is the bed elevation (in metres) above mean sea level, and X represents the distance (in km) upriver from the river mouth.

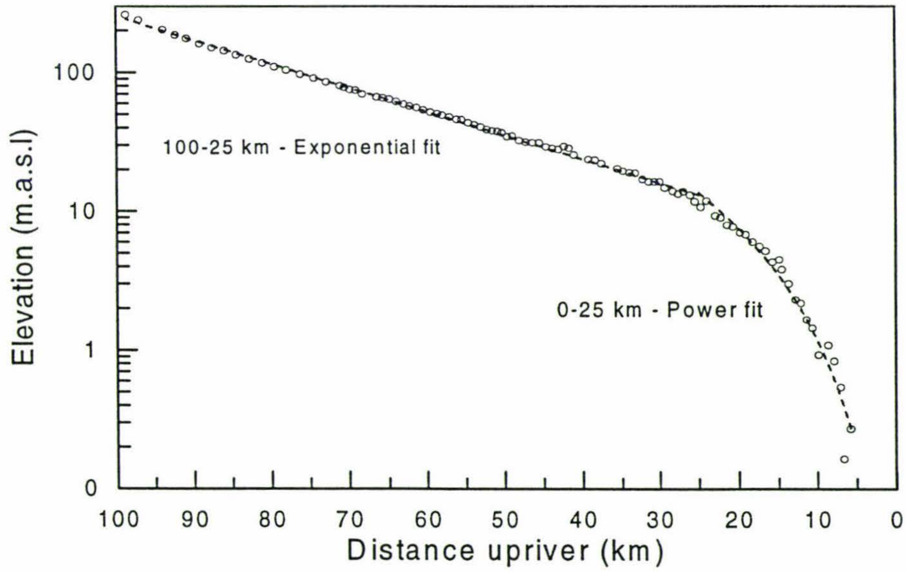


Figure 5.35 The longitudinal profile of the Waipaoa River, showing the mathematical function that best describes the profile.

By the application of Ohmori's (1991) model to the Waipaoa River, the lower ~25 km reach of the Waipaoa River exhibited a transportational profile, where degradation was the primary physical process occurring. The remaining length of the Waipaoa River exhibited a depositional profile. This relationship between the longitudinal profile and the morphological state of the river was confirmed by cross section data obtained by the GDC over the past 50 years. The location in the Waipaoa River that corresponded to the transition between the exponential and power functions was coincident with the extent of degradation that occurred during Cyclone Bola, upstream of the river mouth. The remainder of the river was unequivocally aggradational. Ohmori's model therefore generally applied to the Waipaoa River, and was used to further characterise the sediment transport processes in the lower reaches of the Waipaoa River. The shape of the longitudinal profile has not changed significantly over the last 50 years, as shown in Figure 5.36.

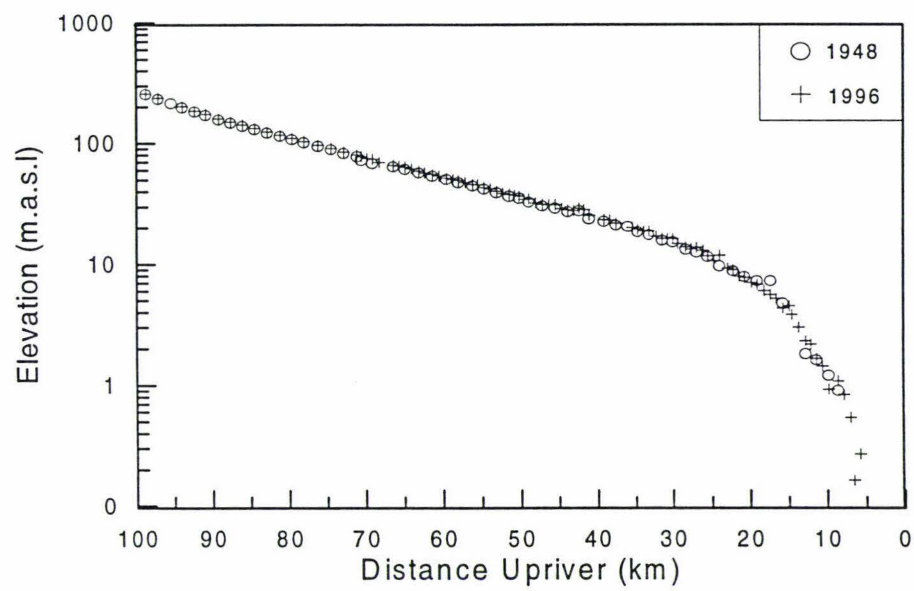


Figure 5.36 The longitudinal profile of the Waipaoa River as measured in 1996, and 1948. Although aggradation has occurred, the overall shape of the profile has remained the same (Data source: GDC).

Bed slope and grain size; The longitudinal variation in local bed slope and reach slope are presented in Figure 5.37. Reach slope declined exponentially downstream as a function of distance according to the equation

$$\log S_r = 0.035*X - 8.21 \quad (5.3)$$

where S_r represents reach slope and X represents distance upstream from the river mouth (R^2 = 0.91). Local bed slope also exponentially declined downstream as a function of distance, by the equation

$$\log S_l = 0.029*X - 8.53 \quad (5.4)$$

where S_l represents local bed slope (R^2 = 0.71). The degree of scatter was considerably greater with the relationship between local bed slope and distance upriver. This was a result of the local variation in bed topography between each sampling site. The relationships between reach slope, local bed slope and grain size are shown in Figure 5.38 and Figure 5.39, and the corresponding correlation coefficients between these variables are presented in Table 5.6.

Table 5.6 Correlation coefficients for each particle size fraction with slope.

Particle size	Correlation Coefficients Slope	
	Reach	Local
Subsurface		
D95	0.645	0.439
D90	0.667	0.636
D84	0.643	0.598
D50	0.391	0.419
D25	0.210	0.190
Sorting	0.537	0.436
Surface		
D95	0.517	0.700
D90	0.508	0.659
D84	0.483	0.601
D50	0.465	0.419
D25	0.442	-0.012
Sorting	-0.002	0.272

The coarsest particle size fractions of the bed material consistently exhibited the greatest degree of correlation with the channel slope. This is in close accord with the conclusions of Wilcock (1967), who determined that bed slope was determined by the coarsest, immobile particle size fractions of the bed load. Residual bedload ordinarily was not present in the bed material of the Waipaoa River, with the exception of situations in which coarse material was directly supplied to the channel by mass movement erosion from the adjacent hill slopes. Moderate positive correlation was observed between the coarse particle size fractions (D_{84} to D_{95}) of the subsurface bed material with reach slope. A moderate positive correlation also was observed between local bed slope and subsurface sediment size (D_{90} & D_{84}). Strong positive correlation was observed between surface sediment size (D_{95}) and local slope, and a moderate positive correlation between surface sediment size

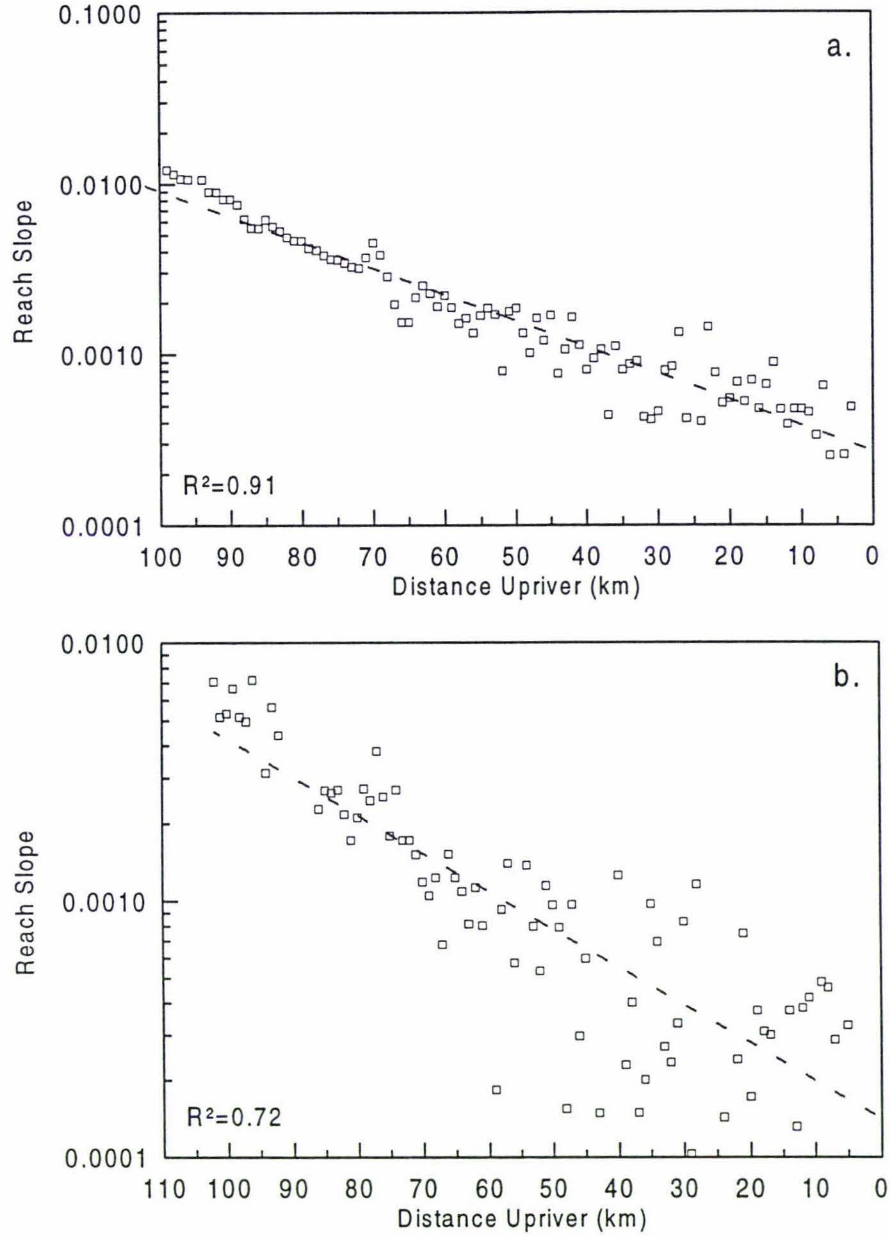


Figure 5.37 Longitudinal variation in a) reach slope, and b) local bed slope.

(D_{90} - D_{95}) and both reach and local bed slope. No significant relationship was observed between local slope and surface bed material sorting, or between surface bed material sorting and reach slope. However, a moderate positive correlation was observed between sorting of the subsurface sediment population and reach slope, and a weak positive correlation was observed between subsurface sorting and local slope. The significant level of correlation that was exhibited between the coarser particle size fractions and the bed slope suggests that the coarsest particles in the bed material reflect the controlling influence of flow competence, through the affect of the bed slope on the shear stress. It therefore appears that the size of the bed material and the bed slope existed in a state of equilibrium, achieved through the process of selective transport.

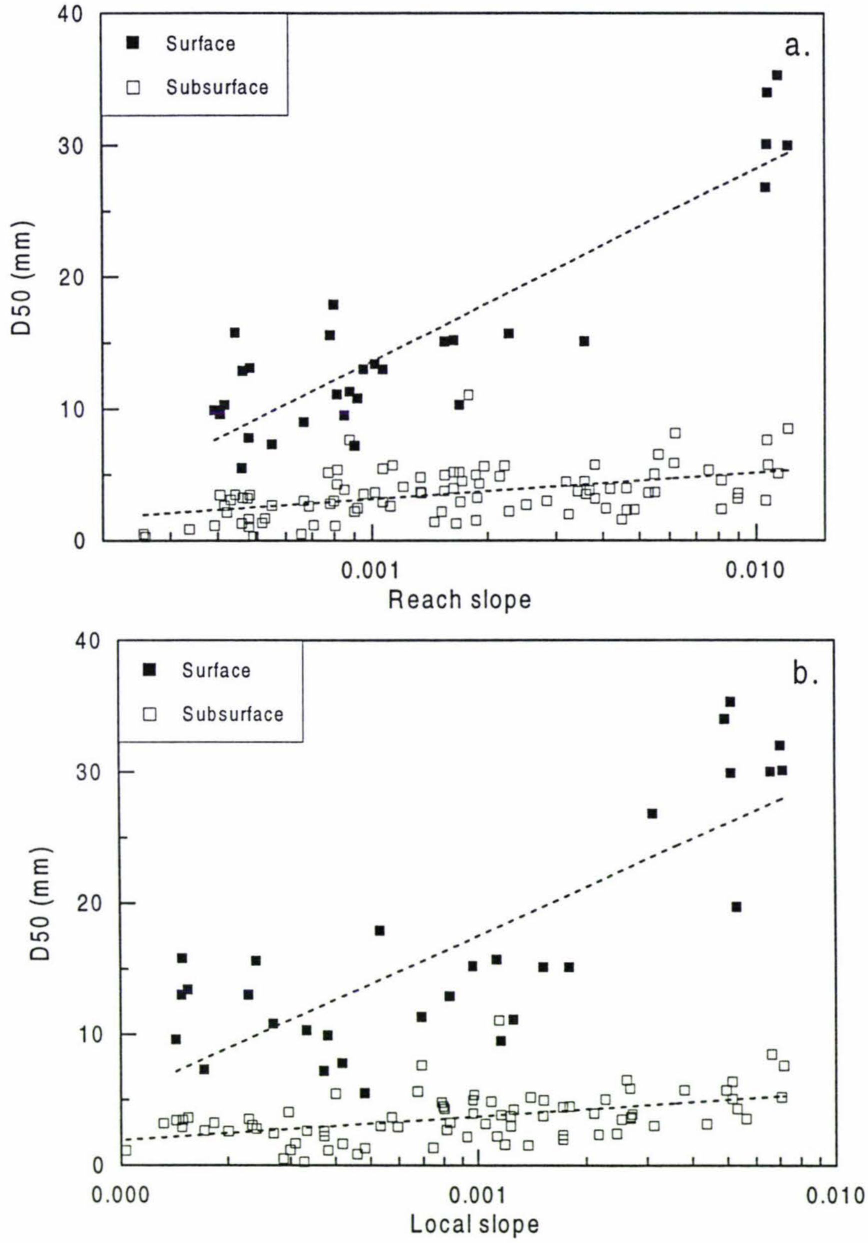
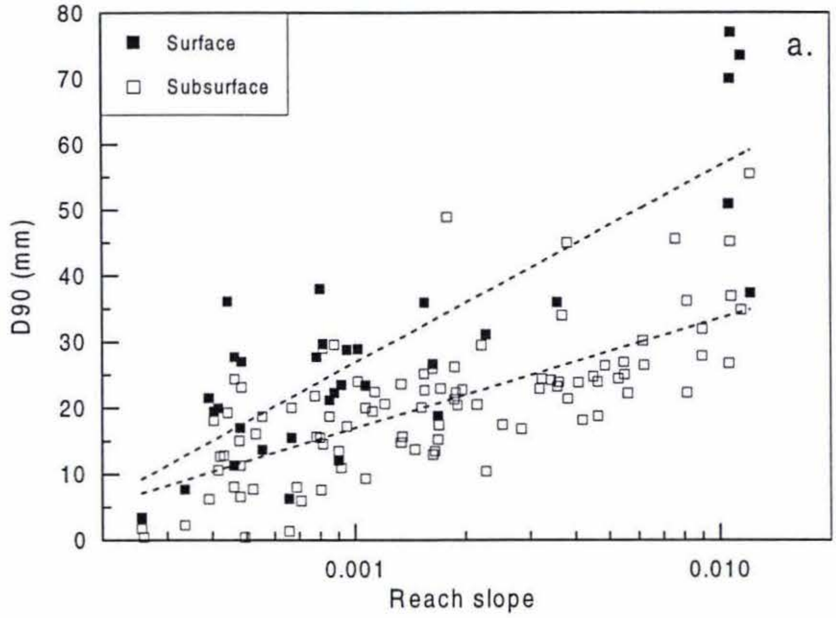


Figure 5.38 The relationship between D_{50} and a) reach slope and b) local slope.

A close relationship existed between channel slope and the bed material particle size in the Waipaoa River, however, depending upon the scale of the river system that was examined, channel slope was considered as an independent or a dependent variable. The above correlations suggest that close relationships existed between the subsurface bed material size and reach slope, and between local slope and the surface bed material size. Subsurface



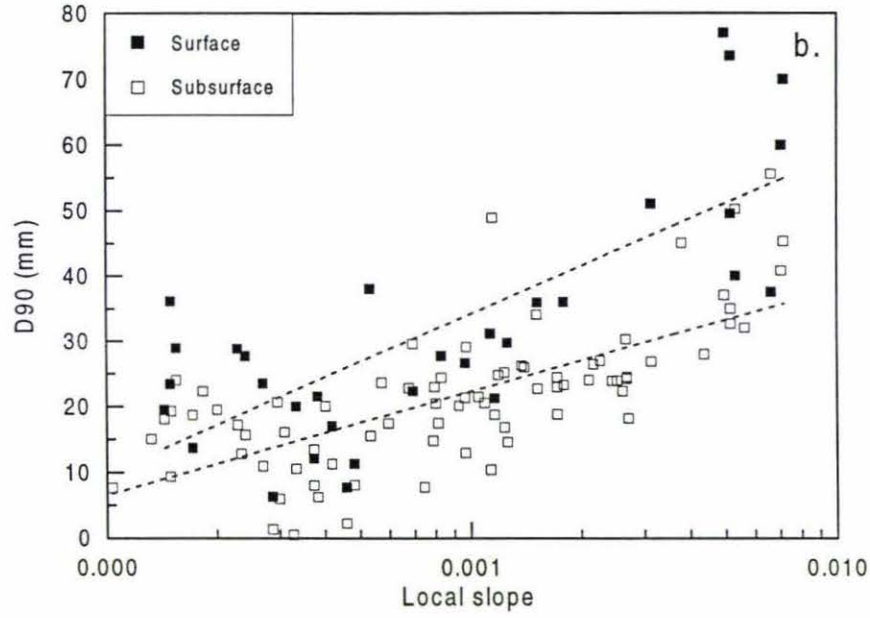


Figure 5.39 The relationships between D_{90} and a) reach slope, and b) local slope.

bed material deposits were considered to be the product of the last major flood experienced in the Waipaoa River, during which extensive bed load transport and mobilisation of the bed material occurred. This flood was Cyclone Bola, in March 1988. The particle size of the subsurface bed material therefore reflected the discharge experienced during that flood. The surface bed material, however, has been subjected to rearrangement and reorganisation by more frequent, but lower magnitude flood events, during which the water surface slope more closely reflected local variations in the bed surface topography.

It is proposed that during peak stages of large magnitude floods, in which extensive bed load transport occurred, the water depth was great relative to the local differences in bed slope, and the water surface slope primarily was determined by the overall reach slope. Local differences in bed slope were effectively evened out, and the size of the subsurface bed material deposited reflected the overall flow competence in the reach, which was dependent upon the reach slope. As the flow receded and the water depth decreased, as well as during more frequent, lower magnitude flood events, the water surface slope probably more closely reflected the local variations in bed slope, which caused local differences in the shear stress. Local differences in surface bed material particle size therefore are explained by the local variations in the shear stress, that were caused by local bed topography variations.

Slope and drainage area relationships; Contributory drainage basin area upstream of each sampling site was employed here as a surrogate for discharge, following the work of Hack (1957). Contributory drainage basin area increased in a stepwise manner in the downstream direction, due to the confluence of tributaries with the main channel. Between tributaries, a smooth rate of increasing drainage basin area was observed. The relationship between channel slope and contributory drainage basin area is presented in Figure 5.40. The effect of tributary inputs are clearly seen on this plot.

In the Waipaoa River, a strong negative correlation (R^2 = -0.797) was observed between reach slope and drainage area, as well as between local slope and drainage area (R^2 = -0.705). Reach slope exhibited a slightly higher correlation coefficient to drainage area than local slope, as a result of the greater degree of scatter in the local bed slope data obtained in the field. The negative correlation coefficients indicate that channel slope decreased downstream as contributory drainage basin area increased. By implication, discharge also increased downstream at a similar rate. Similar relationships were observed by Hack (1957), in streams of Virginia and Maryland, as well as by Penning-Rowsell and Townshend (1978), in streams of southeast Scotland. These relationships suggest that channel slope was partially controlled by the drainage area, and by implication, the mean annual discharge at each sampling site. Bed slope appears to decline in the downstream direction in response to the increase in discharge, indicated by the increasing drainage area. This implies that a lower gradient was required to transport the bed material due to the increase in discharge. A very strong negative correlation coefficient ($R^2 = 0.867$) also was observed between the surface particle size and drainage basin area.

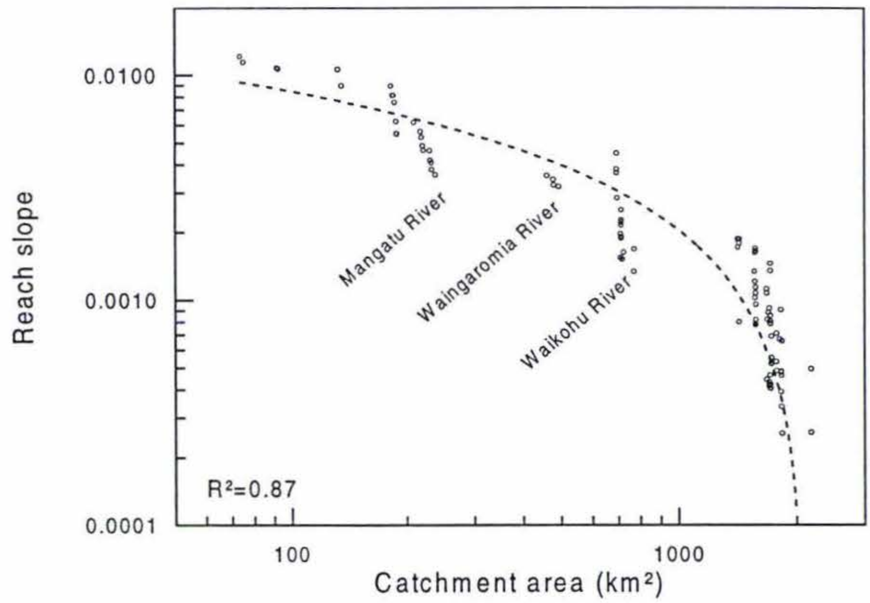


Figure 5.40 Relationship between drainage area and reach slope. The logarithmic fit is expressed by the equation $S_r = -0.0023 * \log (D_a) + 0.021$, where S_r is reach slope, and D_a is the drainage area upstream from each sampling site.

Multiple correlation between area, size and slope; Following the methodology of Hack (1957), multiple correlation was carried out between slope, particle size (D_{50} and D_{90}) and contributory drainage basin area, employing drainage basin area as a surrogate for discharge. Correlation was performed using contributory drainage area and the ratio of particle size to slope. Very strong positive correlation was observed between both reach and local slope, and subsurface D_{90} and D_{50}, with drainage area. The relationship is shown in Figure 5.41. The highest correlation coefficient ($R^2 = 0.907$) was obtained between reach slope/$D_{50\ subsurface}$ and drainage area. Reach slope/$D_{90\ surface}$ had a moderate negative correlation to drainage area. Multiple correlation between particle size, slope and drainage area (discharge) consistently achieved higher correlation coefficients than were observed between any two of the variables by themselves.

The above relationships suggest that a high degree of mutual adjustment existed between the particle size of the bed material, the bed slope, and the mean annual discharge (implied from drainage area relationship) at each sampling site in the Waipaoa River. This also suggests that the decline in the size of the bed material in the downstream direction was directly related to the decline in flow competence along the river channel, and also implies that if the discharge was held constant, the bed slope would increase directly as the size of the bed material increased (Hack, 1957).

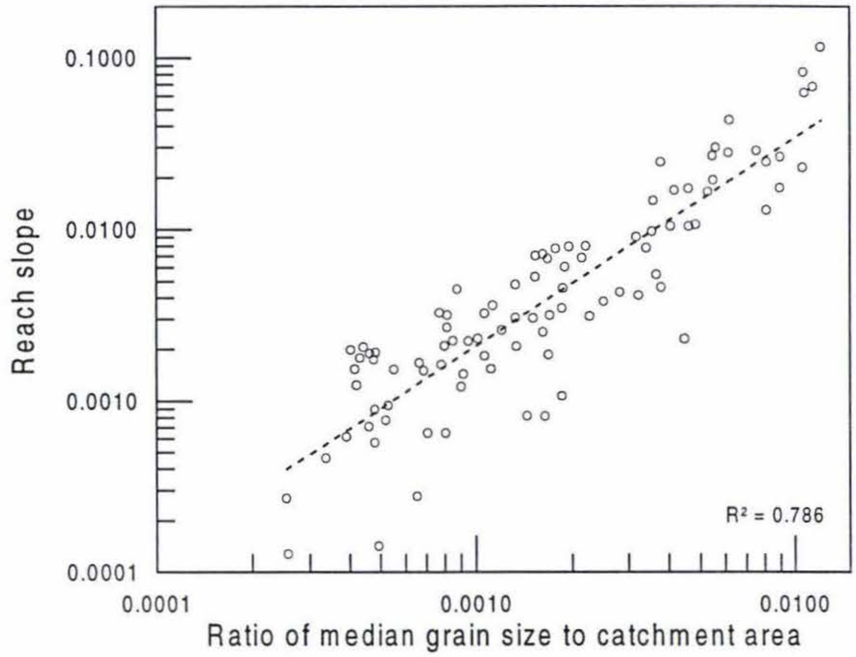


Figure 5.41 The relationship between the ratio of D_{50} to drainage area, and reach slope.

Slope and river morphology; The Waipaoa River can be divided into several reaches defined on the style of river morphology exhibited through the reach. Average slopes, widths and depths observed within each of the reaches are presented in Table 5.7. The longitudinal variation in the width and depth of the Waipaoa River are shown in Figure 5.42. The highest bed slopes were encountered in the upper braided reaches, and bed slope decreased downstream through the transitional reach, and then to the meandering reach. The lowest slopes were encountered downstream from the gravel-sand transition, near the coast. In the Waipaoa River, a complicating factor was that the downstream changes in river morphology were such that bed slope was also expected to decrease downstream.

The morphology exhibited by different reaches in the Waipaoa River can be considered to be the product of the interaction between the size and amount of sediment supplied to the reach, and the discharge available to transport the supplied material. In the upper reaches above the gorge, where the coarsest sediment was supplied to the channel at the greatest rate, the river exhibited a wide, shallow cross section, that was braided in planform pattern. Also, in this reach the available discharge was insufficient to rework the sediment. Wide, shallow channels typically are considered to be less hydraulically efficient than narrow, deep channels, and consequently more energy is dissipated by bed friction (Penning-Rowsell & Townshend, 1967). A steeper slope therefore is required to transport the bed material through a channel that exhibits a wide, shallow cross section. A confounding circumstance in the upper reaches of the Waipaoa River was the presence of a narrow gorge downstream of 91 km, which acted as a choke point, and prevented the movement of sediment downstream. This aspect of the channel morphology, and the influence of the gorge on the river system is discussed in section 5.7.

Table 5.7 Characteristic slopes observed within the different reaches of the Waipaoa River that exhibit differing channel morphologies, and the corresponding average channel width and depth through that reach.

Reach		Slope		Cross section	
Morphology	km	Local	Reach	Width	Depth
Braided	102-92	0.0055	0.0105	301.1	2.14
Gorge	91-77	0.0022	0.0050	55.3	3.54
Transitional	76-56	0.0013	0.0025	106.3	3.26
Single thread	55-8	0.0006	0.0008	83.7	7.90
Sand bed	8-0	0.0002	0.0002	197.2	5.03

A moderate positive correlation coefficient ($R^2 = 0.71$) was observed between local bed slope and the ratio of width to depth in the Waipaoa River. The positive correlation coefficient indicates that as the channel width decreased, and the channel depth increased in the downstream direction, channel slope decreased accordingly. The river channel slope was therefore partially controlled by the channel cross-section shape and planform pattern.

Local bed slope and reach slope decreased considerably at the upstream end of the gorge. This reduction in slope can be thought of as channel adjustment in response to the dramatic transformation of channel cross section. Above the gorge the channel was very wide and shallow, and through the gorge the channel was narrow and deeper. Consequently, a lower slope was required to transport the supplied material due to the greater hydraulic efficiency of the channel through the gorge reach. Another factor which contributed to the decrease in slope was the marked decline in bed material particle size, which was shown earlier to have a strong positive correlation with local bed slope, and a moderate positive correlation with reach slope.

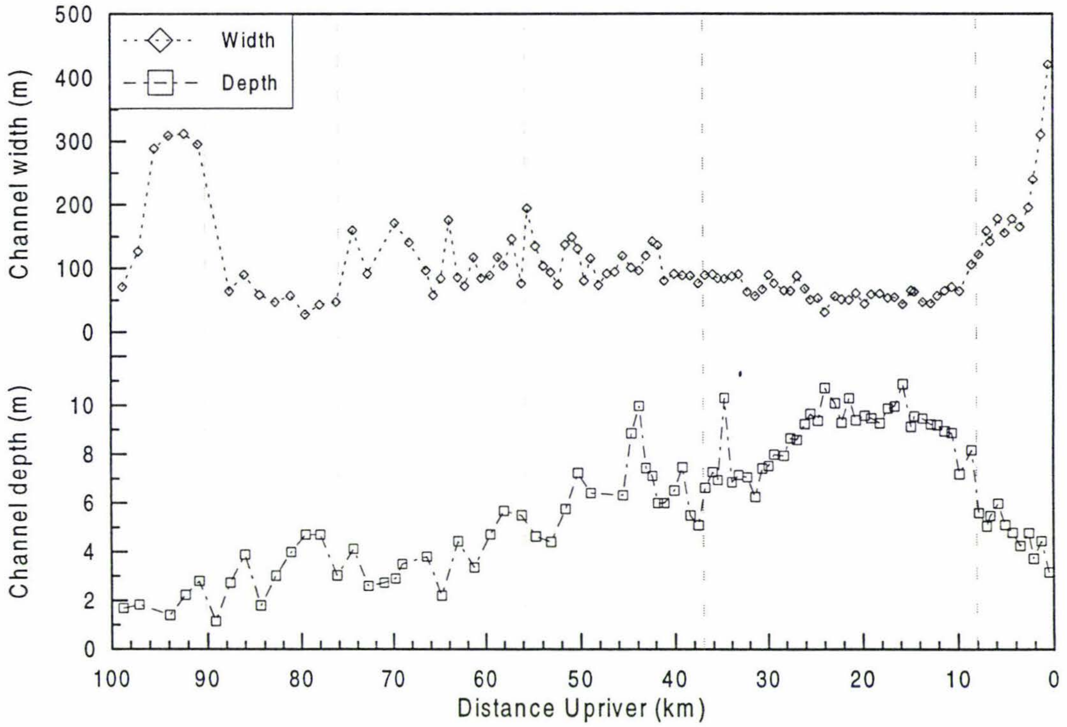


Figure 5.42 The longitudinal variation in width and depth along the Waipaoa River.

In the downstream direction, the channel cross section shape generally became more hydraulically efficient and the discharge available with which to rework and transport the supplied bed material was considerably greater. Consequently, the channel planform pattern underwent a series of transformations in the downstream direction, and lower slope was required to transport the material supplied to successive downstream reaches. The meandering reach was the most likely to exist in a state of equilibrium between the sediment supply from upstream and the available discharge, although the presence of aggradation in the channel suggests that this equilibrium was not quite attained.

5.6 Pebble Shape

Maximum projection sphericity (MPS) and particle form are the only two quantitative parameters discussed in this section. Interpretation of the remaining particle shape parameters that were investigated lead to identical conclusions as those drawn from the interpretation of MPS trends. Pebble shape is a function of pebble lithology and size (Krumbein, 1941; Sneed & Folk, 1956). The relationship between pebble shape and size, and pebble shape and lithology therefore must be clarified before meaningful conclusions could be drawn regarding pebble shape changes in the downstream direction.

Pebble size and shape; In the Waipaoa River, MPS increased as a function of increasing grain size when all size fractions and lithologies together were compared. No significant relationship (coefficient of determination $R^2 = 0.02$) was found, however, between size and MPS within individual half-phi particle size fractions. In all parts of the Waipaoa River, sandstone and siltstone exhibited increasing MPS as a function of increasing grain size. Argillite exhibited decreasing MPS as grain size increased in the upper reaches, but increasing MPS with increasing grain size in the lower reaches. The bladed particle shape dominated all particle size fractions for each lithology, in all parts of the river. At the downstream end of the river system, small pebbles exhibited a higher degree of rounding than large pebbles. The relationship between particle size and rounding in the lower reach is illustrated in Figure 5.43.

Shape and lithology; Sphericity was evaluated from the combined data from sites in the upper (100-80 km), middle (70-40 km), and lower (30-10 km) reaches of the Waipaoa River. In every reach the lithology exhibiting the greatest degree of sphericity was different for individual particle size fractions. All differences in MPS and particle form are significant at the 95 % confidence level, unless stated otherwise.

In the upper reaches of the Waipaoa River, the lithology that exhibited the highest degree of sphericity was argillite in the 16-22 mm particle size fraction, and siltstone in both the 22-31 mm and 31-45 mm particle size fractions. However, no significant difference was found between sandstone and siltstone pebbles in the 31-45 mm particle size fraction. In

Figure 5.43 Roundness of particles in the 22-31 and 4-8 mm particle size fractions from the 18 km sampling site, illustrating that smaller particles exhibited a higher degree of rounding than larger particles in the lower reaches of the Waipaoa River. This suggests that selective transport is an important process occurring in the Waipaoa River.

the middle reaches, argillite pebbles exhibited the greatest degree of sphericity in the 16-22 mm particle size fraction, argillite and sandstone pebbles in the 22-31 mm particle size fraction (no significant difference between 22-31 mm sandstone and argillite pebbles), but no significant difference was found between sandstone, siltstone, and argillite pebbles in the 31-45 mm particle size fraction. In the lower reaches, argillite pebbles exhibited the greatest degree of sphericity in both the 16-22 mm and the 22-31 mm particle size fractions, and no significant difference was found between sandstone, siltstone or argillite pebbles in the 31-45 mm particle size fraction. There were insufficient particles (1 or 2) in the 45-63 mm, or 63-90 mm particle size fractions to warrant examination. When all pebbles >16 mm were compared, argillite exhibited the greatest overall sphericity, followed by sandstone, and then siltstone. Sandstone and siltstone exhibited very similar MPS, and there was no significant difference between these two lithologies.

The bladed particle shape was the most common shape for sandstone, siltstone and argillite pebbles in all particle size fractions. There were, however, slight differences in the percentage of other shaped pebbles that were present. When individual size fractions were compared, no particular lithology consistently exhibited greater sphericity, or a greater abundance of particle shapes, besides the bladed shape. If, however, all pebbles greater than 16 mm were grouped together, argillite exhibited the greatest degree of sphericity, followed by sandstone, and then siltstone. Lithological control on particle shape was important, but the lack of well defined trends suggest that particle abrasion during transport is not an important process that contributed to downstream fining in the Waipaoa River. If abrasion was an important process that occurred in the Waipaoa River, consistent relationships between particle shape and lithology would have been expected. Alternatively, the input of fresh material, primarily from bank erosion, obscured trends that would otherwise have been expected.

Downstream changes in pebble shape; In order to eliminate the controlling influences of pebble lithology and size, and decipher tends of changing pebble shape in the downstream direction, individual particle size fractions and lithologies were studied. The longitudinal variation in pebble sphericity (MPS) for sandstone, siltstone and argillite particles are shown in Figure 5.44.

No significant change in MPS was observed with distance for any lithology, within any size fraction. These results were consistent with the findings of Huddart (1994), who reported no downstream changes in particle shape in a braided outwash system in Iceland. Argillite showed a slight increase in flatness downstream, but this trend was not significant at the 95 % confidence level ($R^2 = 0.2$). The relatively greater change in MPS of argillite pebbles can be explained by the relative size effect discussed earlier. Sphericity decreased with increasing particle size in the upper reaches, but increased with increasing particle size in the lower reaches. Effectively, this means that smaller argillite pebbles became relatively more spherical downstream, and larger argillite pebbles became relatively less spherical downstream. The combined effect of which was to enhance the variation of MPS for argillite pebbles in the downstream direction. Sandstone and siltstone pebbles both exhibited increasing MPS with increasing size, in all parts of the river, so the relative size effect was absent.

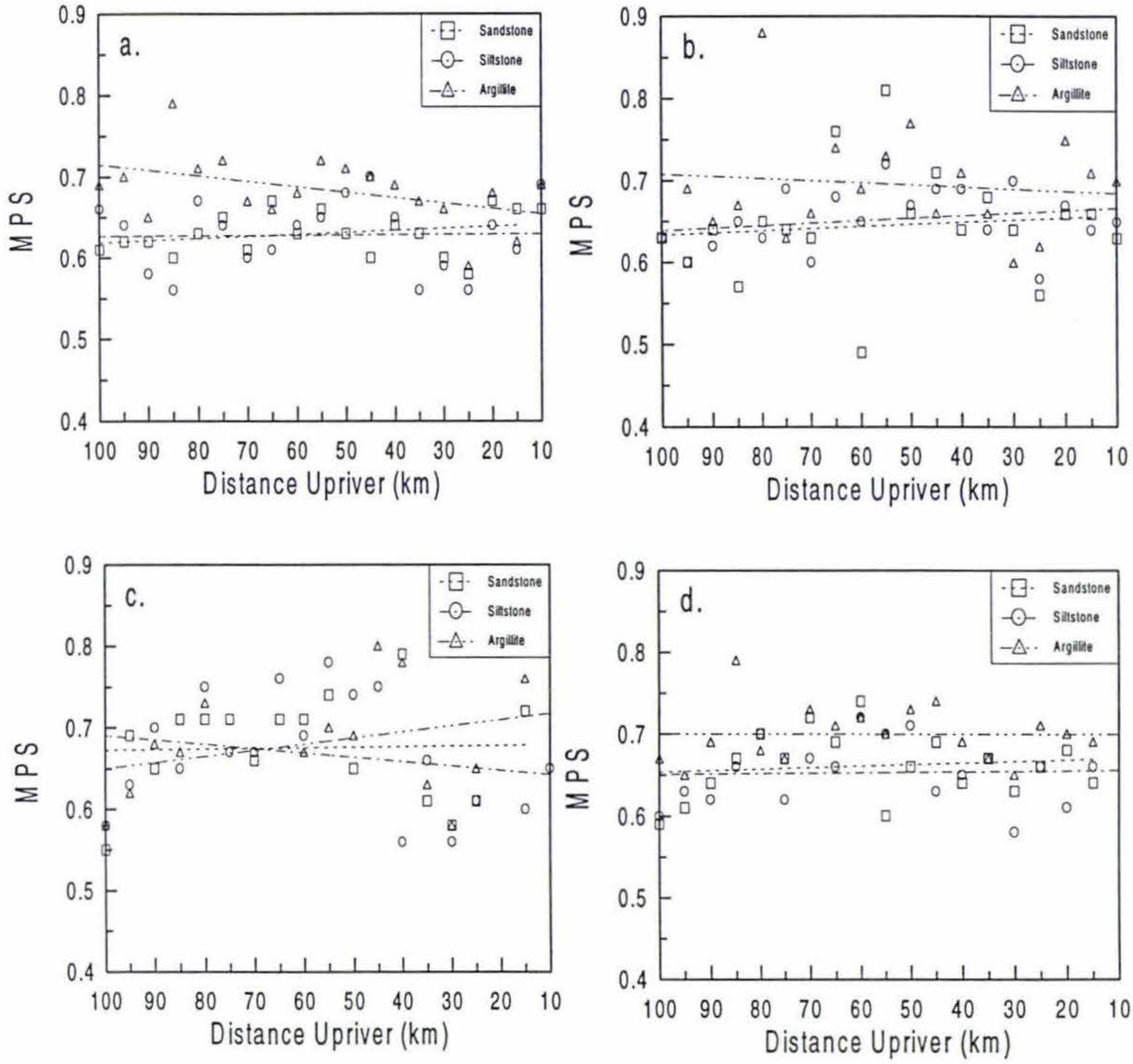


Figure 5.44 Longitudinal variation in maximum projection sphericity of the a) 16-22, b) 22-31, c) 31-45, and d) >16 mm particle size fractions.

When all size fractions >16 mm were compared together, sandstone, siltstone and argillite pebbles exhibited a very slight increase in MPS downstream, although this increase was not significant at the 95 % confidence level (R^2<0.04 for all lithologies). Sandstone, siltstone, and argillite pebbles exhibited identical downstream rates of sphericity increase (~-0.0002), suggesting that abrasion had a negligible effect on particle shape in the Waipaoa River. If abrasion was an important process occurring in the Waipaoa River, the durability differences between rock types was expected to be enhanced, and different rock types were expected to exhibit different rates of downstream variation in pebble sphericity.

Average particle shapes obtained from the 16-22 mm particle size fraction at each fifth sampling site are presented on a Folk Form diagram in Figure 5.45 The bladed shape dominated in all positions of the river, for all lithologies and particle size fractions. A similar dominance of bladed particles of natural river pebbles was observed by Sneed and Folk (1956). They found a strong tendency for the intermediate axis to be exactly halfway between the length of the long and short axes, for all rock types. No mathematical or graphical reason could be found for this concentration, and it was concluded that pebbles have a natural tendency to fall within the bladed shape category (Sneed & Folk, 1956). In the Waipaoa River, no consistent trends of changing average pebble shape were observed in the downstream direction.

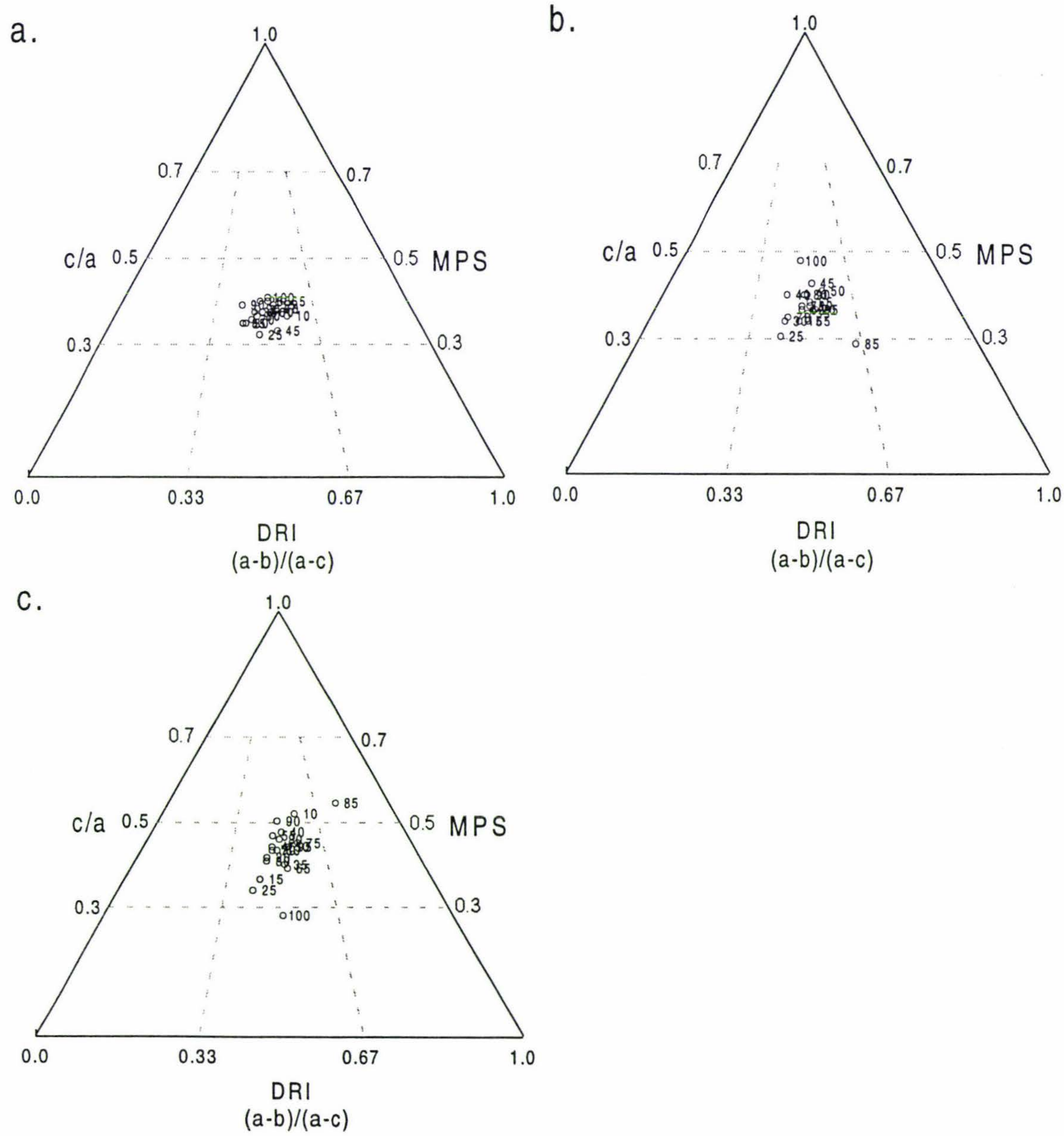


Figure 5.45 Average particle shapes from each fifth sampling site, for a) sandstone, b) siltstone,, and c) argillite, presented on Folk Form Triangles (Folk, 1947).

Pebble roundness unquestionably increased downstream in the Waipaoa River, and is illustrated qualitatively in Figure 5.46. A relatively high degree of roundness was achieved within the first 10-20 km of transport. Abrasion therefore did occur in the Waipaoa River, however, it was not an important process that contributed to either particle shape alteration or downstream fining. Abrasion is an inevitable process that occurs during fluvial transport.

Figure 5.46 The downstream increase in particle roundness for sandstone, siltstone, and argillite pebbles in the 22-31 mm particle size fraction. Pebbles are compared from a site in the upper reaches (102 km), and in the lower reaches (18 km) of the Waipaoa River. The downstream increase in roundness is clearly evident.

5.7 Effect of Geology on The Waipaoa River

Several important investigations have highlighted the importance of the catchment geology as a factor controlling the bed material and channel character exhibited by rivers and streams (Hack, 1957; Miller, 1958; Brush, 1961). An attempt was made to relate the observed channel characteristics and patterns of bed material variation in the Waipaoa River to the influence of the catchment geology.

At the upstream end of the gorge (92 km) the Waipaoa River underwent a dramatic change in planform pattern and morphology. The channel width decreased from 271.5 m to 57.6 m (refer to Figure 5.42), and the local bed slope decreased from 0.005 m km^{-1} to 0.0023 m km^{-1}, at the transition from the braided to the gorge reach. Local bed slope decreased dramatically near the top of the gorge, but instead of decreasing at the upstream end, coincident with the reduction in width as would be expected, the bed slope declined from a point 2-3 km downstream from the top of the gorge. The reduction in bed slope was a consequence of the decreasing bed material size, which also declined 2-3 km downstream from the beginning of the gorge. It was likely that channel adjustment in the form of decreased slope also occurred in response to the decrease in channel width, and the consequent increase in competence. A lower slope therefore was required to transport the bed material through the gorge reach.

The size of the bed material decreased markedly near the upstream end of the gorge due to the combination of a number of factors. Coarse gravel and cobbles were observed on the bar surfaces on the inside of meander bends, at slightly higher elevations on the point bar than the current level of the active low-flow channel. These coarse gravel and cobble sized particles were probably deposited during Cyclone Bola, in March 1988. The downstream limit of the large particles was related to the distance of transport during that single storm event, which in turn may have been related to the decrease in bed slope downstream. No such magnitude storm has been experienced in the Waipaoa River since 1988. Particles derived from the fine-grained sedimentary lithologies of the upper reaches are subject to fracturing processes, by the incidence of desiccation while exposed on the river bed. The coarse particles transported part way through the gorge existed in various states of desiccation/tessellation on the upper bar surfaces. It is proposed here that the coarse particles deposited in the lower parts of the channel were subsequently fractured into smaller particles, and transported through the river system. However, the particles situated on the higher parts of the point bar surfaces have not been subjected to flows of sufficient magnitude to initiate motion, and consequently have remained on the bar surface and have been subjected to desiccation processes. The supply of coarse gravel and cobbles comprised of Cretaceous siltstone and argillite was effectively diminished at the top of the gorge, at the lithological boundary between the Cretaceous and Miocene sediments. Downstream from 92 km, coarse material was delivered to the channel by mass movement erosion directly into the channel, however, the material was predominantly composed of poorly consolidated mudstone. Consequently the particles were rapidly abraded during fluvial transport.

It appears that the channel has adjusted itself to the imposed sediment load, which rapidly decreased in size due to the combined effect of the spatial representation of lithologies within the catchment, limiting the supply of coarse, particles, and to the physical weathering processes that occur within the individual particles, that act to reduce the particle size, without the necessitation of transport. Examination of the particle size distribution curves above, through and below the gorge (Figure 5.47), suggests that the 0.25-11 mm particle size fractions were preferentially transported through the gorge, while the particle size fractions >16 mm were relatively depleted. The <250 μ fraction also was depleted downstream. Possibly this reflects the entrapment of the finest particles within the bed material of the braided reaches in the upper catchment, while the < 250 μ fraction was relatively more efficiently transferred through the single thread reaches, without experiencing deposition to such a degree. The preferential entrainment through the gorge of the 0.25-11 mm particle size fraction represents the effect of size selective transport, and suggests that the gorge influenced or controlled the size of material that was transferred from the upper reaches to the middle and lower reaches farther downstream.

The rate of bed level aggradation declined dramatically also at the top of the gorge. In the period 1948 to 1960, the rate of bed level aggradation above the gorge was 150-250 mm yr^{-1}, and the rate rapidly declined in the downstream direction (refer to Figure 5.48). At

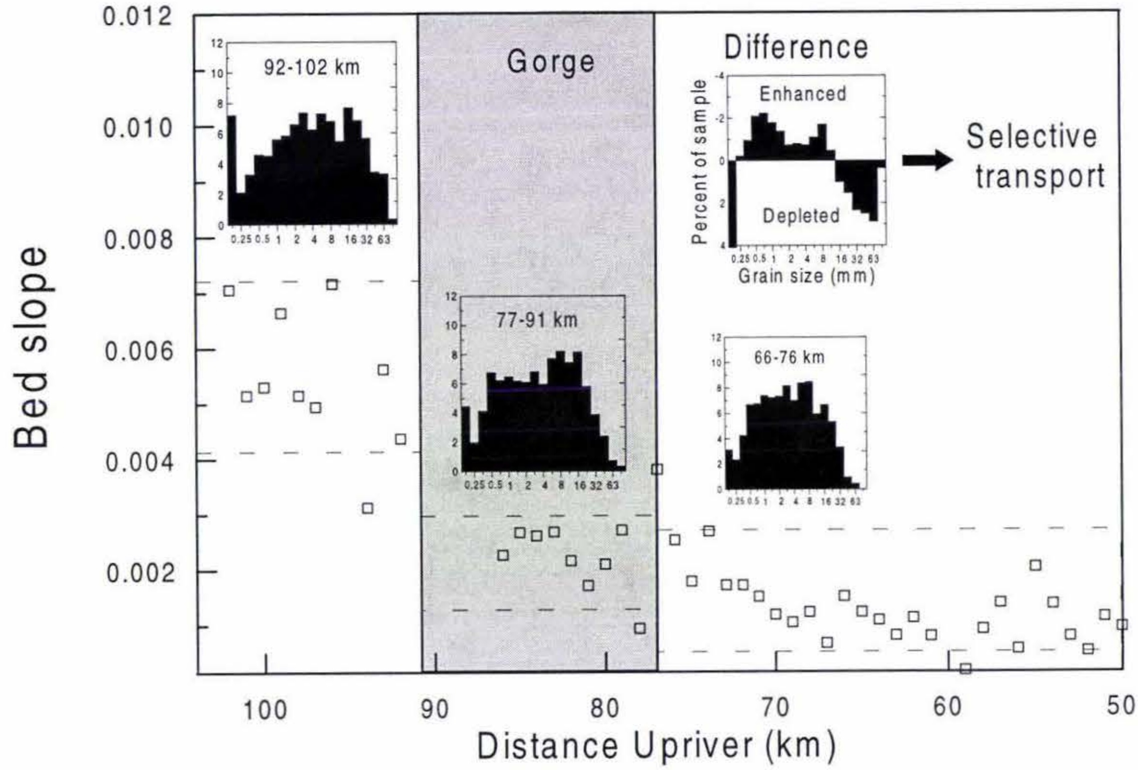


Figure 5.47 Changing particle size distribution curves upstream, through and downstream of the gorge, shown in relation to local bed slope.

~86 km, the rate of aggradation had declined to ~50 mm yr^{-1}, and the rate was maintained at approximately this value for the majority of the remaining length of the Waipaoa River. The rapidly declining rate of aggradation downstream from the top of the gorge suggests that the gorge also was controlling the quantity of sediment that was transported from the upper reaches, and that was supplied to the middle and lower reaches downstream.

During the process of aggradation, material from the surface is transferred to the subsurface, (Toro-Escobar *et al.*, 1996). This means that all material supplied to the gorge and below once was exposed at the surface, and was subjected to physical weathering processes. For large particles (approximately > 90 mm in diameter) to be transported from the upper reaches in a relatively intact state means that the particles must have been buried or underwater for the majority of the transport distance (and time) from the headwater reaches. In an aggradational setting, it is difficult to transport the subsurface material onto the surface downstream. A possible mechanism is during large storm events that may have caused degradation of the channel.

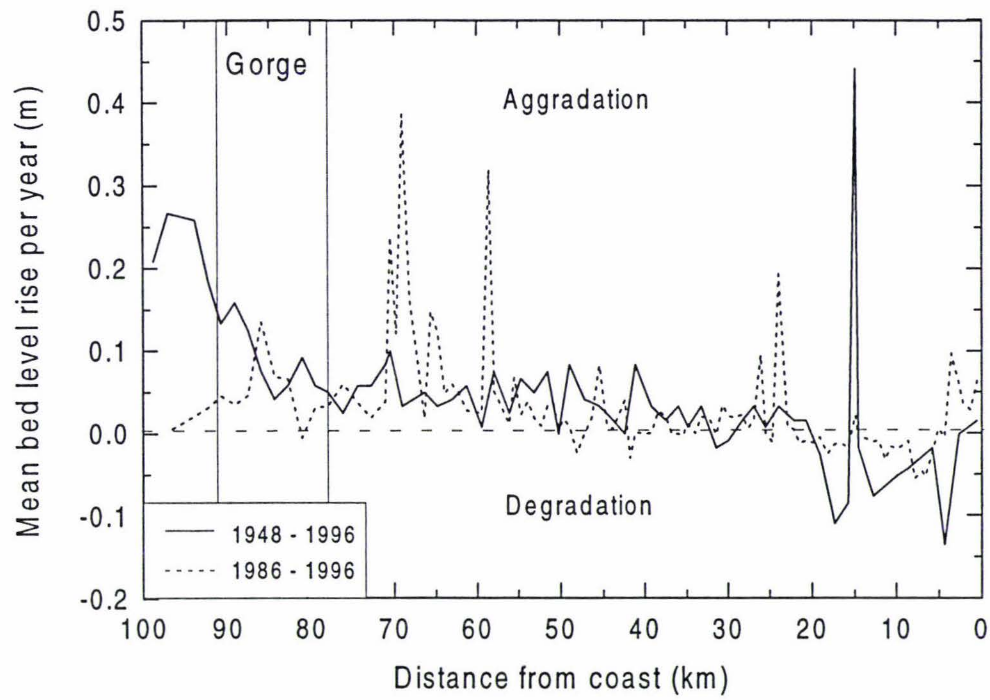


Figure 5.48 The longitudinal variation in aggradation rate in the period from 1948 to 1960, as well as from 1986 to 1996. Note the dramatic decrease in aggradation rate downstream from 92 km, in the period from 1948 to 1960, when aggradation was occurring at a much faster rate (Data source: GDC).

The presence of the gorge in the upper reaches effectively constitutes a choke point, or a filter, that has controlled the size and amount of sediment that was transferred to the downstream reaches. The morphology of the Waipaoa River has been shown to be a product of the relationship between the size of the bed material, the quantity of sediment that is supplied to the individual reaches, and the quantity of water available with which to rework the sediment. Consequently, the morphology of the river was indirectly controlled by the catchment geology and the presence of the narrow gorge between 92 and 77 km. The river underwent a dramatic change at ~92 km from a wide, shallow, multiple-thread braided configuration in the upper reaches, to an essentially single-thread, meandering river in the lower reaches. In the lower reaches the Waipaoa River exhibited a considerably narrower and deeper channel, although the channel did have a tendency to exhibit a multiple thread configuration at low flow.

5.8 Summary of Results

Bed material lithology; The bed material of the Waipaoa River predominantly was composed of Cretaceous sandstone, siltstone and argillite particles supplied to the channel from the upper reaches. Comparable rates of downstream particle size decline (fining coefficients) were exhibit by all three lithologies. No particular particle lithology increased in proportion downstream at the expense of another particle lithology. Similar maximum particle sizes were observed for all lithologies, in all parts of the river, with the exception of sandstone, which was the dominant lithology for the upper 5 km. Sandstone dominated the bed material of the upper 5 km reach because the sediment supplied from the Tikihore and Waimatau streams was dominated by the Tikihore Formation (Mazengarb *et al.*, 1991). An identical rate of MPS increase downstream was exhibited for all lithologies also. Although the increase in MPS was not statistically significant, the fact that the rate of change was identical for particles of all lithologies suggests that abrasion was not an important process that contributed to downstream fining in the Waipaoa River.

Abrasion appears to have had a minimal effect on the bed material of the Waipaoa River, despite the friable nature of the sediment supply. Abrasion, however, did occur in the Waipaoa River, and is of importance locally, where soft mudstone entered the channel from the erosion of mudstone bluffs and cliff faces. The local importance of abrasion was evidenced by the rapidly diminishing proportion of soft mudstone downstream from sediment inputs, and the low proportion of mudstone present in each sample. Soft mudstone rarely was encountered in the finer particle size fractions. Instead mudstone particles from bank erosion were presumed to brake down into silt and clay sized particles that were readily incorporated in the suspended sediment load. Selective transport appears to be the dominant mechanism of downstream fining in the Waipaoa River, and has operated to minimise the differences between the different particle lithologies in the downstream direction.

Basalt and other volcanic rocks encountered in the Waingaromia, Waikohu and Waihora rivers were not present in significant quantities in the main channel. The absence of the igneous lithologies in the Waipaoa River bed material was explained by the combination of two processes. Firstly, the dilution of the igneous lithologies by the abundant supply of sandstone, siltstone and argillite from upstream, and secondly, the fact that coarse bed material from the Waingaromia, Waikohu and Waihora rivers was not transferred to the main Waipaoa River channel.

Particle size; The Waipaoa River is a gravel bed river for most of its length, however, the bed material was dominated by fine sediment that was supplied to the river by mass movement and gully erosion of siltstone, mudstone and argillite terrains. The predominance of fine sediment in the Waipaoa River was reflected by the relatively fine median particle size (D_{50}) over the length of the entire river (<6 mm), and the low fining coefficients obtained for particle size fractions finer than the median particle size. The low fining coefficients obtained for particle size fractions finer than the median suggests that fine particles were transported through the Waipaoa River system with little modification by selective transport and abrasion processes.

There were interruptions to the general trend of downstream fining in the Waipaoa River. These were accounted for by sediment inputs to the channel from tributaries or bank erosion. In the upper reaches, sediment supplied from tributary sources were relatively more important, in terms of influencing the bed material of the Waipaoa River, than those from riparian sources. In the middle and lower reaches, however, sediment supplied from hill slopes directly linked to the channel dominated over sediment supplied from tributary streams. The gravel fraction in the bed material in the Waingaromia, Waikohu and Waihora rivers did not appear to be transferred to the Waipaoa River. No apparent effect on the bed material in the Waipaoa River was observed downstream from tributary streams in the middle reaches, but the bed material clearly was influenced by the input of sediment from non-fluvial sources. Sediment inputs from bank erosion generally were localised in nature. Fine sediment was incorporated into the bed load or the suspended load, whereas coarse sediment remained in the immediate vicinity of the sediment input. Coarse sediment may subsequently have been broken down by desiccation processes while exposed on the river bed.

Similar sediment inputs from hill slopes directly linked to the main channel in the upper reaches in streams in the Queen Charlotte Islands, British Columbia, were described by

Rice and Church (1996), who referred to the streams as strongly coupled. Strongly coupled streams, or reaches of streams, lack well a defined alluvial floodplain, consequently material is directly transferred from the adjacent hill slopes to the river channel (Rice, 1994). The particle size of the bed material in the streams studied by Rice and Church (1996) fluctuated in response to the sediment inputs and non-fluvial sediment storage controls (log jams, alluvial fans etc), the combined effect of which was to prevent the development of systematic downstream trends in bed material texture. The size of the bed material essentially was independent of systematic sorting and abrasion processes in the downstream direction (Rice & Church, 1996). Strongly coupled reaches are expected to become less common downstream, as fluvial activity begins to dominate over hill slope activity. The development of an alluvial floodplain, and the relatively greater discharge available with which to rework sediment inputs reduces the likelihood of strongly coupled reaches existing farther downstream (Rice, 1994).

Downstream fining in the Waipaoa River was concentrated in the particle size fractions coarser than the median particle size (D_{50} - D_{95}). This indicated that the coarsest particle size fractions of the bed material represented the limiting condition of stream competence. Surface sediment bed material exhibited a rate of downstream fining comparable to the subsurface, however, the finer particle size fractions of the surface bed material (D_5 - D_{35}) exhibited the greatest rate of downstream fining. The faster rate of downstream fining exhibited by the finer particle size fractions (D_5 - D_{35}) of the surface bed material reflected the greater entrainment frequency of the smaller, more mobile particles.

In the Waipaoa River, the rate of downstream fining generally decreased downstream. Improved characterisation of the downstream decline in particle size therefore may be achieved by employing a negative power function, rather than an exponential function. Individual reaches in the Waipaoa River behave as individual sedimentation environments, each with their own set of processes that interacted to produce distinct rates of particle size decline.

Downstream fining; In the Waipaoa River, the rate of downstream fining generally decreased downstream. Individual reaches in the Waipaoa River were subject to distinct processes which created varying rates of downstream fining. The most rapid rate of downstream fining was exhibited by the upper braided reaches, from 102 to 92 km. Here the sediment supply rate from both tributary streams and hill slope erosion was high, but insufficient discharge was available to rework the sediment, consequently aggradation occurred. In this type of environment, the river system was effectively competence limited, and hydraulic sorting dominated over abrasion. These conclusions are comparable with the findings of Shaw and Kellerhals (1982). The greater rate of downstream increase in the sorting coefficient (standard deviation) in the upper 10-12 km reach suggests that sorting was more efficient in producing downstream fining in close proximity to the sediment source, compared with farther downstream, where the supply of sediment from upstream was more likely to be in equilibrium with the quantity of sediment transferred through the reach. The rate of particle breakdown also was greatest in the upper braided reach, and this was demonstrated by the relatively high percentage of <250 micron particles in the particle size distribution curve. The common occurrence of tessellated particles on the bed surface, from the action of desiccation, also attributes to the rapid rate of particle breakdown above the gorge.

In the upstream portion of the gorge reach, from 92 to ~87 km, the size of the bed material decreased dramatically. This marked decline in bed material particle size was attributed to the combination of a sediment supply control, as well as to the downstream limit of large particles deposited during a single large magnitude storm event in March 1988. The sediment supply was effected by two factors through the gorge reach; the diminished supply of coarse argillite and siltstone particles, effective at the boundary of the Cretaceous and Miocene sediments at the upstream end of the gorge; and the supply of predominantly fine particles from the erosion of the poorly consolidated Miocene mudstone that underlies the gorge reach. The downstream limit of the coarse gravel and cobbles during Cyclone Bola may in turn have been related to the declining flow competence as the bed slope decreased downstream, alternatively, the downstream limit of these particles was determined by the distance the particles were transported during the storm event. In the very upper reaches of the gorge, which were supplied with coarse argillite and siltstone particles, fragmentation by desiccation also may have been important, but it can be assumed that the importance of fragmentation decreased markedly downstream from this point.

Throughout the transitional reach, from 77-60 km, selective transport assumed the dominant role. However, the plentiful supply of fine material from the erosion of poorly consolidated mudstone bluffs and hillslopes further complicated the pattern of downstream fining. Abrasion may have been of importance locally in the transitional reach, in situations where soft material was transferred to the river channel directly from bank erosion. Downstream from sediment inputs, mudstone particles were rapidly abraded and rarely were encountered in the >16 mm particle size fraction. The percentage of 'soft' lithologies comprising the >16 mm particle size fraction declined rapidly when the supply of 'soft' mudstone to the channel diminished, downstream from the point where a continuous floodplain had developed (~55 km). The rapid decline in the proportion of 'soft' particle lithologies was attributed to the local importance of abrasional processes in the Waipaoa River.

The downstream meandering reach of the Waipaoa River exhibited the lowest rate of bed level aggradation and was the most likely of all the reaches to exist in a state of equilibrium, in which the sediment supplied to the reach was roughly equalled by the sediment transport capacity of the river. In this type of environment, hydraulic sorting became less efficient, and the role of abrasion became more important in producing downstream fining. This reach, including the meandering and flood control scheme reaches of the Waipaoa River, can be further subdivided by the occurrence of degradation in the lower ~25 km reach. A faster rate of downstream fining, comparable to that observed in the upper reaches above the gorge, was observed in the lower 25 km reach. Abrasional comminution during fluvial transport therefore was assumed to be the dominant process in the lower 25 km reach. The gravel-sand transition, which occurred approximately 8 km upriver from the coast, was explained by the selective deposition of the largest particle size fractions as a result of the decreasing flow competence in the channel. The rapid decline in flow competence was occasioned by the combination of the large increase in hydraulic radius, that was associated with the tidal limit, as well as the local base level control imposed on the river by the sea, causing the consequent decline in bed slope.

No systematic trends in changing bed material size were observed in the Waipaoa River over the last 50 years. The lack of temporal trends in particle size suggest that the pattern of downstream fining in the Waipaoa River was well established by 1950, greater than 50 years following the initial reports of channel change. The overall pattern of downstream fining was set up early in a laboratory flume, and was maintained as the gravel front migrated downstream, and the bed aggraded (Paola *et al., 1992).* A similar observation also was made by Hoey and Ferguson (1994), who produced a numerical model that simulated downstream fining in gravel-bed rivers. However, a temporal variation in the bed material particle size downstream of the gravel-sand transition in the Waipaoa River has been illustrated. The presence of the gravel-sand transition in the Waipaoa River appeared to be associated with the occurrence of major storm events. During large floods, such as Cyclone Bola, gravel was transported through the lower sand bed reach and deposited in Poverty Bay. However, during periods of 'normal' flow, gravel was progressively deposited in the reaches above the gravel-sand transition, with only sand and silt sized material transported further downstream. The gravel-sand transition in the Waipaoa River was occasioned by a large increase in cross sectional area associated with the tidal limit, as well as the decline in bed slope experienced as the river approached the fixed base level imposed by the sea. Bidirectional flow and increased salinity in the lower 10 km reach probably also encouraged the deposition of fine material, and enhanced the transition from a gravel-bed to a sand-bed channel. Similar gravel-sand transitions are expected to occur in the Waingaromia, Waikohu, and Waihora rivers near their confluences with the Waipaoa River as the result of the backwater effect created by the flow in the Waipaoa River.

Slope and downstream fining; In the Waipaoa River, both reach and local bed slope decreased exponentially in the downstream direction, and this was reflected by the concave longitudinal profile of the river. The majority of the longitudinal profile (from 102 to 25 km) also was described by an exponential decline downstream, however the lower 25 km reach was described by a downstream decrease according to a power function. The transition between the exponential and power functions was coincident with the extent of degradation experienced in the lower reaches during large magnitude flood events.

Close relationships have been demonstrated between the particle size of the bed material and the bed slope, however, depending upon the scale of slope examined, different aspects of particle size and slope were important. Good correlation was observed between reach slope and subsurface bed material size, and also between local slope and surface bed material size. These relationships were explained by the different hydraulic conditions which lead to the deposition, or rearrangement of the individual sediment populations. The subsurface bed material was deposited in response to the last large flood experienced in the river, during which extensive bed load transport and mobilisation of the bed material occurred. During these conditions, local differences in bed slope and topography effectively were 'drowned out' as the water depth became great relative to the topographic differences, and the water surface slope (and therefore the flow competence) reflected the overall reach slope conditions. However, during smaller events, in which bed load transport did not occur, the surface particles probably were rearranged and reorganised. During these hydraulic conditions, local differences in bed topography were more likely to cause local differences in flow competence, which account for local differences in surface bed material size.

The above observations were comparable with the conclusions drawn by Penning-Rowsell and Townshend (1967), who determined that surface sediment size exhibited better correlation to local slope, rather than reach slope. Penning-Rowsell and Townshend (1967) also concluded that reach slope exhibited better correlation to drainage basin area, which was employed as an index of discharge, rather than bed material size. Bed material size, both on the surface and in the subsurface, were closely related to bed slope, but it was difficult to determine which variables were independent or dependent. Hack (1957) considered that bed material size and bed slope existed in a state of dynamic equilibrium, in which variation in one variable automatically caused a change in the other, in order to absorb the effects of change.

The highest correlation coefficients consistently were achieved between the coarsest particle fractions of the bed material and slope, indicating that the largest particles in the bed material represent a limiting condition of flow competence. Selective transport of the finer particles fractions therefore was an important process that occurred in the Waipaoa River. The importance of selective transport is further supported by the high correlation coefficients observed between the reach slope and the sorting of the subsurface bed material.

Strong (negative) correlations also were observed between both slope (reach and local), and bed material size, with drainage basin area. The coarsest particle size fractions of the subsurface bed material appear to be adjusted to the imposed discharge conditions, while all particle size fractions of the surface bed material exhibited strong correlation to drainage area (~discharge). The strong relationships between all surface particle size fractions and drainage area were not surprising when it is recalled that the surface particle size fractions represent the coarsest particle size fractions in the subsurface bed material. However, the best relationships were achieved when size, slope and drainage area were combined. Very strong positive correlations were observed. The high degree of correlation between size, slope and drainage area suggested that the slope of the channel and the size of the bed material existed in a state of dynamic equilibrium, and that both the slope and bed material size were in turn adjusted to the imposed discharge conditions in the Waipaoa River. Close relationships therefore were expected between the longitudinal profile of the river, and both the bed material particle size, and the channel slope.

Pebble shape; In the Waipaoa River, pebble shape is a function of particle size and lithology, but no consistent relationships between size, shape, and lithology were established. A greater degree of variation was observed between different particle size fractions at a single sampling location, compared to that which was observed in a single particle size fraction after 100 km of fluvial transport. The lack of pebble sphericity alteration downstream for individual particle size fractions, as well as the identical rate of downstream variation in sphericity for all particles >16 mm suggested that fluvial abrasion had little influence on the shape of particles in the Waipaoa River bed material. The high degree of rounding accomplished within a relatively short distance illustrated, however, that abrasion does occur in the Waipaoa River. The downstream increase in particle roundness was expected because of the relatively soft and unsound nature of the sediment supply, and is a natural consequence of fluvial transport. At the downstream end of the Waipaoa River, smaller particles exhibited a higher degree of rounding than larger particles, further augmenting the notion that selective transport assumed the dominant role in producing downstream fining in the Waipaoa River.

The size, shape, and lithologic composition of the bed material along the length of the Waipaoa River has been characterised in the preceding discussion. Downstream trends in the size, shape, and lithologic composition of the bed material also have been identified, and an attempt has been made to interpret and explain the observed trends. Relationships between the bed material and reach slope, local slope, the longitudinal profile and catchment area also have been explored. All particle size fractions in the surface and subsurface sediment populations exhibited downstream fining, however, downstream fining was most rapid in the coarser particle size fractions. Interruptions to the general downstream fining trend were related to tributary and riparian sediment inputs in the upper reaches, and to sediment inputs from bank erosion in the middle and lower reaches. Several lines of evidence, that include the downstream trends in each rock type, the lack of pebble shape alteration, the greater rate of downstream fining exhibited by coarser particle size fractions, and the close relationships between the bed material particle size and the longitudinal profile, indicate the overall dominance of selective transport in producing downstream fining in the Waipaoa River. However, other processes, such as the sediment supply, particle fragmentation, abrasion, or the influence of the catchment geology, may have exerted a significant control on downstream fining in specific reaches in the Waipaoa River.

The particle size of the bed material in the Waipaoa River was affected downstream of the confluence with tributaries such as Te Weraroa Stream. Throughout the middle and lower reaches, however, sediment from mass movements originating from bluffs and hillslopes that were directly linked to the Waipaoa River channel were relatively more important than the sediment supplied from tributary streams. No difference in the particle size of the Waipaoa River bed material was observed downstream from the confluence with the Waingaromia, Waikohu, or Waihora rivers. It therefore was presumed that the gravel fraction of the bed material contained in these streams was not transferred to the Waipaoa River. However, in the middle and lower reaches, the bed material particle size clearly was influenced by the input of sediment from bank erosion sources. Sediment inputs from bank erosion generally were localised in nature. Fine material was incorporated into the bed load or suspended load and transported through the river system, whereas coarse material remained in the immediate vicinity of the sediment input, and particle fragmentation by desiccation occurred.

There is a high degree of correlation between the bed material particle size and the longitudinal profile of the Waipaoa River, and a close relationship between the coarser particle size fractions and bed slope. These relationships suggest that the downstream decline in particle size primarily was a manifestation of the downstream decline in flow competence in the river channel, as a result of the downstream decline in slope. This notion is further underpinned by the greater degree of correlation that was observed between slope and the coarsest particle size fractions in the bed material, and is consistent with the concept that the largest particles in the bed material reflect the limiting condition of competence (Brierley & Hickin, 1985). The close relationships observed between reach slope and the sub-surface particle size, as well as that observed between local bed slope and surface particle size, also were explained in terms of the hydraulic conditions which prevailed during the deposition or subsequent re-arrangement of the respective sediment populations. Strong correlation was observed between the drainage area (and therefore average annual discharge) and the particle size (particularly the surface particle size). However, a greater degree of correlation was achieved between slope and the ratio of particle size to catchment area, than was achieved between the individual variables. The enhanced correlation between particle size, slope and drainage area suggests a level of mutual adjustment between the longitudinal profile and the particle size, to the available discharge.

The absence of any well defined downstream trends in the shape and lithologic composition of the bed material also is indicative of selective transport processes in the Waipaoa River, rather than abrasional processes. The three primary pebble lithologies, sandstone, siltstone, and argillite, exhibited similar fining coefficients, similar downstream decline in the proportion of the entire sample, and similar maximum as well as average particle size at a sampling location. No lithology was consistently coarser, or increased in proportion downstream at the expense of other rock types. These observations are consistent with the notion that selective transport effectively minimises the differences between pebbles of different lithologies, so that all lithologies exhibit comparable trends and rates of downstream particle size decline (Huddart, 1994). The lack of downstream changes in the maximum projection sphericity and particle form of the >16 mm particle size fraction further substantiates the conclusion that abrasion had a negligible influence, and that overall, selective transport assumed the dominant role in producing downstream fining in the Waipaoa River.

The Waipaoa River is a gravel-bed river, but the system was dominated by the plentiful supply of fine material from gullies and mass movements, as well as from the rapid breakdown of unsound particles in the upper reaches. Bank erosion in the middle and lower reaches also contributed to the supply of fine material.` Particle size distributions from the subsurface bed material in the Waipaoa River typically were polymodal. The action of selective transport was manifest as the progressive downstream increase in the standard deviation (or sorting) of the bed material particle size distributions. The resultant particle size distributions became progressively more peaked in the downstream direction. As a result of the high proportion of fine material that was encountered along the entire river length, no downstream trends were observed in the skewness of the particle size distributions.

Further characterisation of the downstream fining process in the Waipaoa River was achieved by examination of the downstream evolution of individual particle size subpopulations. This was accomplished by the application of sequential fragmentation transport (SFT) theory (Wohletz, 1996). Prominent particle size subpopulations were identified, as well as the proportion of each subpopulation present. The proportion of each subpopulation changed in the downstream direction. The finer subpopulations declined in proportion downstream at the expense of the coarser subpopulations, and most of the subpopulations exhibited slight downstream fining. These observations indicate that downstream fining in the Waipaoa River also can be explained by the sequential fragmentation of the sediment supplied at the source, and the subsequent modification of the resultant subpopulations by selective transport and abrasion processes. However, the role of particle fragmentation was likely to become less important in the downstream direction.

In the Waipaoa River, the upper, middle and lower reaches of the river, defined on the basis of channel planform pattern, appeared to function as distinct sedimentation environments, each with an individual set of processes that produced specific rates of downstream fining. The highest rate of downstream fining was exhibited in the upper braided reaches, where hydraulic sorting was enhanced by rapid aggradation. Downstream fining also was augmented by the initial rapid breakdown of unsound particles in the first few kilometres of fluvial transport, as well as by the rapid weathering and desiccation of particles while exposed on the river bed. Fragmentation may be important in the very upper reaches of the gorge, but rapidly declined in importance downstream as the particles became smaller, and less prone to physical disintegration. Two aspects of the sediment supply affected the rate of downstream fining in the gorge; firstly the diminished supply of coarse sandstone, argillite and siltstone particles from the Cretaceous rocks underlying the headwater reaches, and secondly, the abundant supply of predominantly fine material from bank erosion throughout the gorge. Throughout the middle reaches, where the river exhibited a tendency to braid at low flow, selective transport was the dominant process. However, abrasion was of local importance in the middle reach at locations at which 'soft' particles were supplied directly to the river channel. Additional fine material also was supplied to the channel by bank erosion of mudstone bluffs adjacent to the river. In the lower, meandering reach of the Waipaoa River, abrasion assumed the dominant role, as the rate of sediment supply from upstream became comparable to the sediment transporting capacity of the river, and slight degradation was exhibited in some of the lower reaches. However, the gravel-sand transition near the coast was accounted for by the selective deposition of the gravel fraction. The gravel fraction was deposited as a result of the rapid decline in flow competence of the river channel. This decline in flow competence was occasioned by an increase in hydraulic radius as well as a decrease in bed slope as the river approached the fixed base level imposed by the sea.

The rates of downstream fining that have been demonstrated in the Waipaoa River are typical for the range of fining coefficients encountered in other river systems. For example, Shaw and Kellerhals (1982) give diminution coefficients in natural rivers within the range from 0.001 - 0.05 km^{-1}. However, individual reaches within the Waipaoa River exhibited fining coefficients that were more consistent with the rates reported by Shaw and Kellerhals (1982) for alluvial fans. The upper reaches (102-92 km), and the lower 25 km reach of the Waipaoa River, as well as the Te Weraroa Stream, exhibited fining coefficients in the range 0.05 - 0.08 km^{-1}. Even higher fining coefficients have been documented in Scotland

(Ferguson & Ashworth, 1991), as well as in a laboratory flume (Paola et al., 1992). Implications are that the rate of downstream fining measured over the entire river length may not accurately reflect the rate of downstream fining that occurs within individual reaches of the river. Instead, processes that are of importance at the local scale (for example; channel constrictions, sediment supply, rapid aggradation, particle fragmentation, or abrasion), may significantly influence the rate of downstream fining. The catchment geology may also influence the pattern of downstream fining.

Downstream fining in the Waipaoa River has been demonstrated to primarily be achieved by selective transport as a result of the declining flow competence downstream. Abrasion, however, clearly is important in the Waipaoa River, particularly at the local scale where soft, unsound lithologies were supplied to the river channel. The importance of other contributing processes, such as particle fragmentation and the sediment supply also have been demonstrated. In a tectonically and geomorphically active catchment such as the Waipaoa River catchment, geological influences, such as the nature of the sediment sources, as well as the channel constriction imposed by the gorge, effect all aspects of the river system, from the pattern and rate of downstream fining, to the downstream changes in river morphology.

This study has emphasized the importance of the sediment supply on the bed material characteristics observed in the Waipaoa River. The high proportion of fine material that was supplied to the channel at the source dominated the bed material characteristics for the entire length of the river. As a result, the bed material was very poorly sorted and lacked any significant downstream trends in skewness. Fine material dominated the particle size distributions curves, and the median particle size was relatively fine over the entire river length. However, the coarser particle size fractions did exhibit a greater rate of downstream fining. This illustrates the importance of selecting the appropriate particle size parameters for investigation in studies of downstream fining. Had only the median particle size been examined, the conclusions drawn would have been markedly different. The lack of downstream trends in the skewness of the bed material illustrates that in situations in which the bed material is dominated by fine sediment, trends that are typically expected in the particles size distribution curves may not occur. This means that models developed to predict the changes in particles size distribution curves in the direction of sediment transport (for example; McLaren & Bowles, 1984), may not be applicable. A high proportion of fine sediment in the bed material also seems to prevent significant armour development. The presence of an armour layer typically has been described as one of the fundamental characteristics of gravel-bed rivers (Parker & Klingeman, 1982; Parker & Sutherland, 1990).

This investigation also has demonstrated that caution is required during the interpretation of ancient fluvial deposits primarily of comprised fine grained sedimentary rocks, such as the Mangatu Formation. This arises because the size of the particles does not necessarily reflect the transporting capacity of the river. Instead, the particle size of the sediment is intimately related to the sediment source, from mass movement and gully erosion of argillite and siltstone terrain. The size of the bed material also appears to be related to the time of exposure of the individual particles. The overall catchment geology, including the structure, rock types and tectonics must be considered when attempting to interpret downstream particle size variations, both in modern and ancient fluvial deposits.

Future research; The fragmentation of particles, through the processes of desiccation while exposed on the river bed poses an interesting topic of research, and one that warrants further investigation. For example, it would be interesting to determine, by experiment, the individual subpopulations formed by the fragmentation of argillite and siltstone particles, and if there is a 'stable' particle size that the particle size subpopulations converge upon. The inherent properties in the rock that determine the time required for fragmentation, as well as the size of the resultant particles, may also be determined.

Further sediment sampling may be required in the Waipaoa River to determine the spatial variability of the bed material particle size at the bar scale. Such information is required to model the behaviour of the river in greater detail.

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Appendix 1 Grid references for the sediment sampling sites

site	grid reference	site	grid reference	site	grid reference
0	398648	51	336931	102	372209
1	390656	52	341922	103	378215
2	384662	53	336916	104	382221
3	387671	54	327918	Waimatau	385223
4	392678	55	325923	Wairangiora	383224
5	395623	56	324932	Tikihore	359204
6	391696	57	323741	Matau	355185
7	383701	58	321950	Matakonekone	348184
8	378709	59	327957	Te Weraroa	348150
9	380718	60	331965	Mangaorongo	348129
10	387725	61	322967	Mangatu1	316028
11	389732	62	321976	Mangatu2	308023
12	384738	63	329972	Waingaromia	347017
13	379741	64	331976	Waihora	376961
14	372742	65	326983	Waikohu	271944
15	374751	66	331985	Te Arai	371691
16	374761	67	338980		
17	376767	68	339988		
18	380772	69	341996		
19	377781	70	351997		
20	374789	71	348003		
21	378797	72	345012		
22	383805	73	338017		
23	380809	74	331022		
24	373815	75	327030		
25	374821	76	317028		
26	380814	77	312035		
27	387818	78	312044		
28	384827	79	310053		
29	382837	80	314057		
30	373839	81	313066		
31	372843	82	319069		
32	379846	83	321076		
33	374851	84	328080		
34	370856	85	329083		
35	374865	86	331091		
36	379873	87	333099		
37	377878	88	332107		
38	372881	89	337110		
39	378888	90	339117		
40	381897	91	343122		
41	385905	92	342130		
42	384914	93	349136		
43	377915	94	348146		
44	373907	95	355152		
45	366903	96	350160		
46	362912	97	353171		
47	362921	98	350180		
48	355927	99	353190		
49	353936	100	359196		
50	344935	101	336205		