UPPER WAITEMATA HARBOUR SEDIMENTS AND THE INFERRED IMPACT OF FUTURE CATCHMENT AND ESTUARY USE CHANGE

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Water Quality Centre
Ministry of Works and Development
Hamilton

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PREFACE

This report is one of a set of 10 Specialist Reports (listed below) on which the findings of the Upper Waitemata Harbour Catchment Study are based.

This and the other Specialist Reports have been heavily condensed to a corresponding set of Reviews which have been published in a format suitable for non-specialist readers, by the Auckland Regional Authority. The central document arising from this work is the Land and Water Management Plan.

The Upper Waitemata Harbour Catchment Study was promoted by the Auckland Regional Water Board although research in many topics was undertaken by other agencies. All the reports are published by the Auckland Regional Authority.

List of Specialist Reports

Ecology of Streams in the Upper Waitemata Harbour Catchment - I Briggs.

Energy Analysis, Upper Waitemata Harbour Catchment Study - G Knox.

Estuarine Ecology, Upper Waitemata Harbour Catchment Study - G Knox.

Land Resources of the Upper Waitemata Harbour Catchment - M R Jessen.

Legal and Planning Considerations in Land and Water Management - Planning Consultants Limited (extensively updated and amended by V Shaw).

Potential Effects of Catchment Use Change on Upper Waitemata Harbour Sediments - T M Hume.

Report on the Freshwater Hydrology of the Upper Waitemata Harbour Catchment - R K Smith.

The Flushing of Pollutants and Nutrients from the Upper Waitemata Harbour - B L Williams and J C Rutherford.

Urban Subdivision and Stormflows:Modelling and Management - P W Williams.

Water Quality in the Upper Waitemata Harbour and Catchment - M R van Roon.

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T.M. Hume

Water Quality Centre, Ministry of Works and Development, Hamilton

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ABSTRACT

This report describes surficial sediments, depositional history and sedimentary processes for the Upper Waitemata Harbour estuary, Auckland, with emphasis on Lucas tidal creek. This information is compared with present day and historical data from other estuaries to predict sedimentological changes likely to result from catchment and estuary use change. These include changes in sediment character and rates of deposition, nutrient distribution, estuarine stability and the effects of engineering works.

KEYWORDS : Waitemata. Estuary. Physical Process. Sediment.

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CONTENTS

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I thank M McLachlan for assistance with the field work, M van Roon (UWHCS) for supplying the stream input sediment data, and B Williams and R Davies-Colley for revising this manuscript.

Palynological work was carried out by M McGlone, Botany Division, DSIR, Christchurch.

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CHAPTER ONE : INTRODUCTION

1.1 BACKGROUND

The Waitemata Harbour plan (Auckland Regional Authority 1975) identified the estuarine area above Hobsonville as being particularly sensitive to pollution (Fig. 1.1 and Plate 1.1). As a result the Upper Waitemata Harbour Catchment Study was initiated in 1976 to study the land and water resources of the catchment in order to provide guidelines for the integrated development, management and protection of these resources and to promote their enhancement for the benefit of the local, regional and national communities.

This report is one of a series of 'Specialist Reports' covering a wide range of topics, that are part of the final series of summary publications from the Upper Waitemata Harbour Catchment Study.

1.2 OBJECTIVES

Estuarine sediment studies were initiated to :

1. establish baseline data against which to monitor future changes in the system;
2. describe sediments and sedimentary processes to provide a reference source for other UWHCS research topics and a variety of UWHCS summary publications (Upper Waitemata Harbour Catchment Study 1983a); and
3. assess the nature, location and magnitude of change in estuarine sediments likely to result from future land and estuary use change.

1.3 SCOPE OF THIS REPORT

Sedimentological baseline studies in Lucas and Hellyers Creeks are detailed in Fry and Hume (1983).

This report summarises surficial sediment character and distribution in the Upper Waitemata Harbour estuary.

The short time frame of the investigations and limited resources did not allow detailed studies of sediment processes. Instead inlet

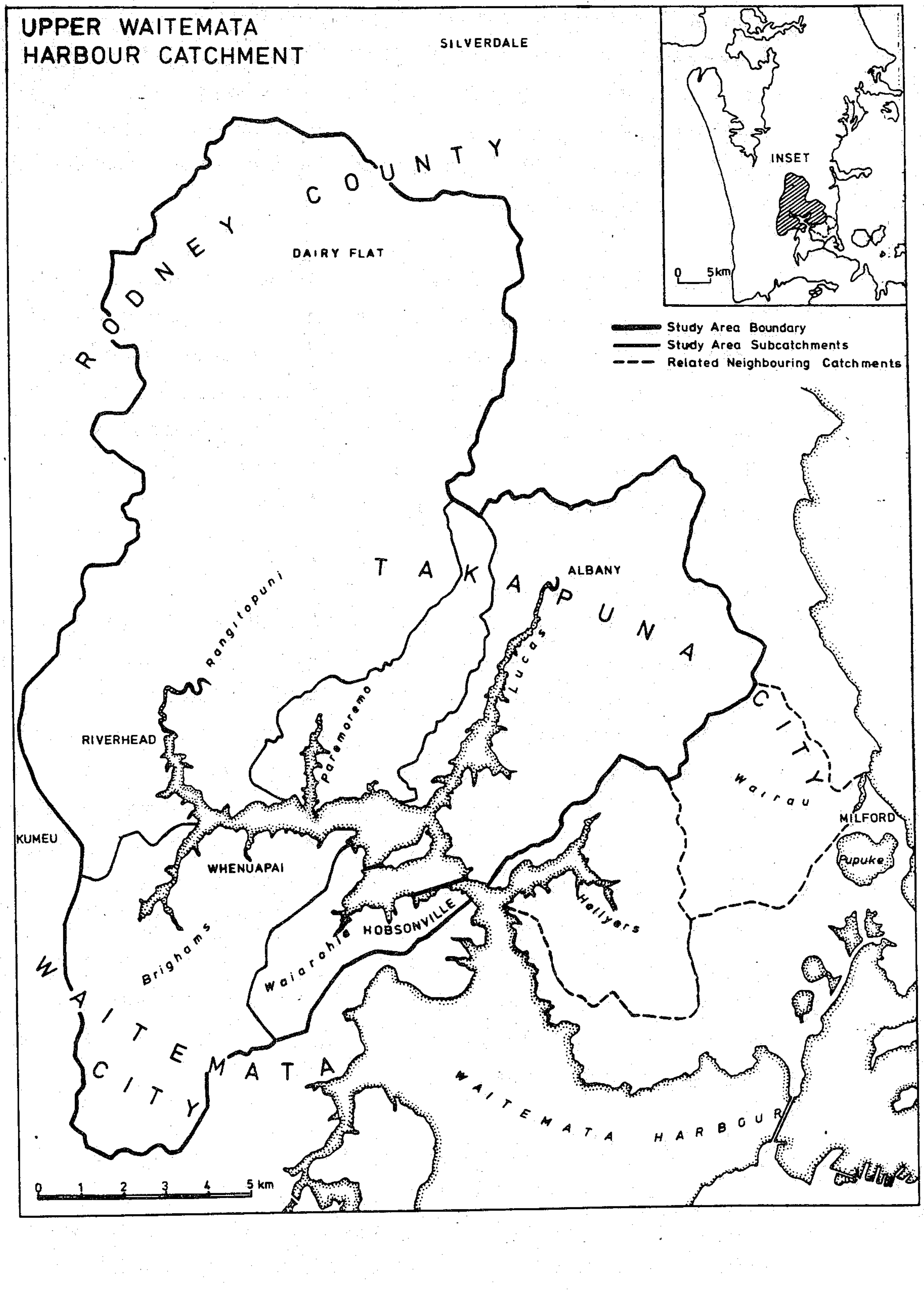

Figure 1 : Upper Waitemata Harbour Catchment, estuary and surrounds

morphology, hydrology, sediment and stream sediment input were examined, and the estuaries likely response to catchment use change assessed by : (1) direct calculation of future sedimentation rates from predicted estuarine inputs, (2) considering the systems past response to change determined from historical records and subsurface sediment data, and (3) by studying the effects of catchment use change on other estuaries.

Sedimentological studies were focused in Lucas Creek because of limited resources, and because it was foreseen (Auckland Regional Authority 1975) that this would be the site where catchment use change would have maximum impact on Upper Waitemata Harbour sediments. The very generalised account of surficial sediments of the wider Upper Harbour estuary is largely based on data collected by other workers, for purposes other than this report.

1.4 ESTUARINE SEDIMENTATION

The composition and distribution of sediments in an estuary is largely determined by the nature of source material and the hydrological regime of the estuarine system. Sediment source initially determines sediment particle shape, size, density and mineralogy, influences organic content, and regulates the frequency and quantity of sediment injected to the estuary. The sediment nature may be modified during transport from source to estuary. The hydraulic characteristics of the estuary, which are primarily determined by river discharge, tidal flow and wind wave action, controls the redistribution of sediment in the system through the processes of deposition (or accretion), erosion (or scour) and transportation. In addition to the hydraulic controls, biological activity can both enhance and inhibit erosion and deposition of sediments.

Possible sources of estuarine sediments include: (1) land erosion by streams, (2) flood tide transport from outer estuary sources, (3) disposal of domestic and industrial effluents and solid wastes, (4) wind transported material from neighbouring sources, (5) decomposition and excretion products of plants and animals.

The most important sediment sources are generally the river and outer estuary sources (McDowell and O'Connor 1977).

The magnitude of sediment input to the estuary from river sources depends on the hydrology, pedology, geology, and land use of the catchment. Supply of sediment is intermittent and determined by the frequency of floods, the particle size of the source material and man-induced factors. Investigations of the effects of high flows on sediment transport showed that for one small catchment in the UK 88% of the total sediment yield was transported by flows that were exceeded only 5% of the time (Humby 1973). Mans influence in the form of removal of the topsoil in an estuarine catchment can result in an increase in sedimentation in the estuary (Strachan 1977), and the presence of engineering structures such as weirs in the river can prevent the passage of bed load material to the lower reaches of the estuary (Humby 1973).

Material derived from estuarine sources outside the mouth (e.g. other arms of the estuary and bank erosion) may be transported by the flood tide into the estuary where it settles in areas of low energy protected from waves and tidal currents.

Estuaries commonly contain sediment in the very fine sand size (125-62 μm) and mud (silt and clay) size (less than 62 μm) ranges (Appendix I). The primary mode of transport of such fine material is as suspended load and it may amount to 75-95% of the total sediment load (McDowell and O'Connor 1977). The distribution of suspended load varies with depth and in general has its highest concentration near the bed and decreases towards the surface (Fig. 1.2). This vertical distribution is altered in highly stratified estuaries by the presence of the salt wedge which alters the vertical density and velocity profiles (Fig. 1.2). Fine sand and coarser material is transported as bed load.

The current velocity at which particles are entrained, transported and deposited depends in large part on particle size (Fig. 1.3). Particles transported as suspension and bed load will be deposited as

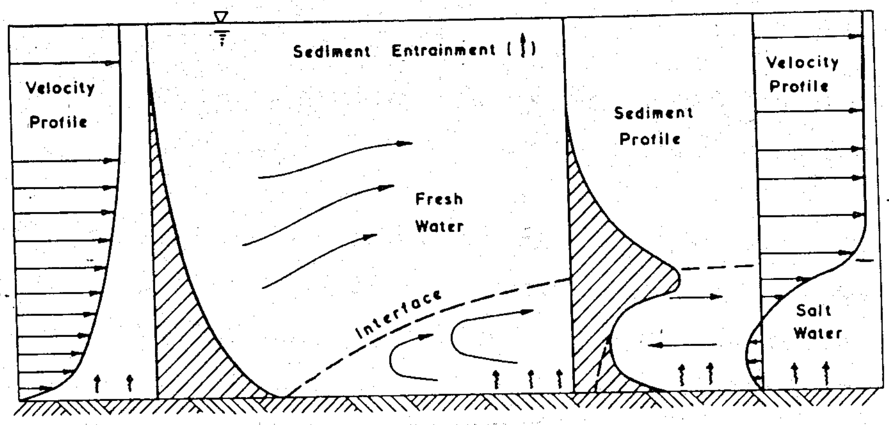

Figure 1.2 : Vertical sediment profiles in stratified flows (from McDowell and O'Connor 1977). For the river inflow shown on the left the sediment concentration decreases towards the surface. In stratified flows where fresh and salt waters meet, the salt wedge alters the velocity and density profile resulting in a sediment concentration high in the water column.

turbulence and current velocities fall below certain values. For cohesionless sands, small particles are transported more easily than larger ones. For cohesive silts and clays the critical erosion velocity increases to clay size indicating that fine sediment can be carried in suspension at velocities lower than those required to erode it. Consequently fine sand particles may be transported into the estuary on the flood tide and deposited at slack water, but the requirement of a higher erosion velocity on the ebb tide to resuspend sediment means that the fine sediments progressively accumulate in cohesive deposits.

Discrete particle behaviour can be substantially modified by flocculation of clay material. Clay particles are commonly less than 2 μm "equivalent spherical diameter", have a density similar to quartz or feldspar but are usually plate-shaped. In the freshwater environment the clays are usually dispersed. On entering the marine environment interaction of the ionically charged clay minerals with dissolved salts in estuarine water causes the clay particles to flocculate into larger size aggregates (Fig. 1.4). The process causes the clays to behave like larger silt and sand size sediment. Deposits formed from floc groups have considerable porosity which slowly

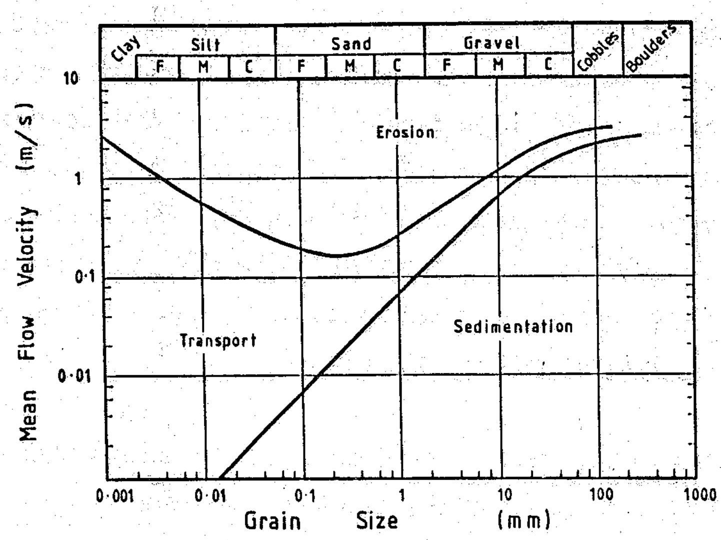

Figure 1.3 : Erosion, transportation and sedimentation velocities (based on depth-averaged velocity) for sediment of various grain sizes. The diagram shows that a particle of 0.1 mm diameter will be eroded from the bed when velocity exceeds 0.2 m/s, is transported when velocity exceeds 0.007 m/s and will be deposited if the velocity drops below 0.007 m/s. Note how erosion velocities increase markedly for silts and clays due to cohesion.

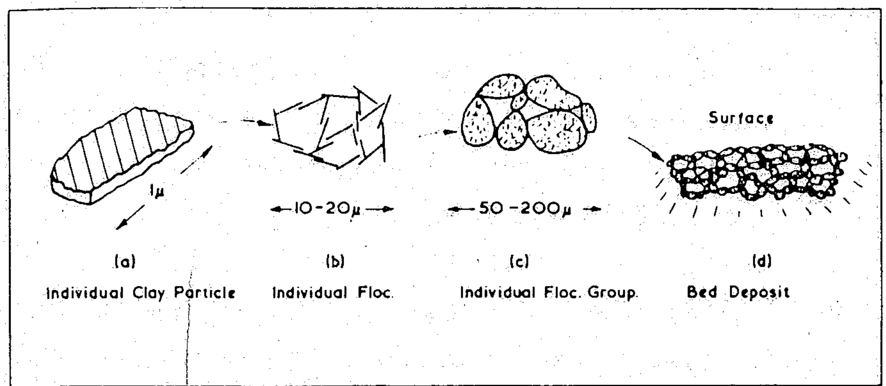

Figure 1.4 : Typical arrangements and sizes of flocs and floc groups (from McDowell and O'Connor 1977).

decreases as the deposit consolidates and the cohesive strength and resistance of the bed against scour increases. The change is reflected in bulk density, for example, freshly deposited material may have densities of 1020-1050 kg/m^3, surface deposits in docks and on estuary margins 1100-1200 kg/m^3, compared with consolidated organic-rich clay with values of 1400-1600 kg/m^3 (McDowell and O'Connor 1977). The process of flocculation is reversible and floccules exposed to freshwater may be dispersed.

Once in an estuary sediments are subject to complex variety of forces that act to sort the sediment and redistribute it within the system or expel it through the mouth. The dominant forces are tidal currents which increase from zero at slack water (high and low tide) to peak at mid tide in response to the semi-diurnal tidal cycle. Maximum current velocities can vary markedly with tidal range being largest for the fortnightly spring tides and lesser for the intermediate neap tides. The flood and ebb of the tides flushes sediment back and forth in the estuary provided there is sufficient velocity to keep the particles in suspension. The sediment particles tend to settle to the bottom under gravitational forces when tidal velocities are low but may be resuspended when velocities increase. The shells of larger animals concentrate in areas of high current velocity as lag deposits and protect finer sediments beneath from erosion. Sediment input increases markedly during storm events but high river inflow can increase bed scour, sediment transport and flushing.

Wave action serves to rework the sediment because high orbital velocities associated with waves are sufficient to suspend most sizes of sediment and once in suspension much lesser tidal velocities can transport the particles.

Biological processes may enhance sediment stability. For instance filter feeding and burrowing animals bind sediment particles as pseudofaeces and faecal pellets, benthic macroalgae grow on surficial sediments binding the grains together and plants reduce current velocities in their vicinity allowing entrained sediment to settle out.

Where physical forces acting on the sediments combine to produce high energy environments (i.e. where current, wave and river inflow effects are intense) the coarser sediments tend to accumulate. Fine muddy sediments predominate in more tranquil low energy situations such as high up on the tidal flats.

The bed of an estuary is constantly changing in response to variations in sediment input, and hydraulic forces such as tidal flows, stream inflow and wave action. Geometric stability refers to the ability of an inlet to return to its initial configuration after a disturbance. An equilibrium inlet is defined here as one which tends to maintain itself in a particular stable configuration. The time-span within which equilibrium is defined is most critical, since it must be long enough to cover all major variations in those parameters which affect sediment motion as well as supply of sediment.

CHAPTER TWO : UPPER WAITEMATA HARBOUR SEDIMENTOLOGY

2.1 PHYSIOGRAPHY AND HYDROLOGY

The Upper Waitemata Harbour estuary (7.4 km^2) is narrow and branching in shape and mangrove bush is common in the more sheltered embayed areas (Fig 1.1 and Plate 1.1).

The bathymetry shows the channel areas of the estuary are composed of a deeper main axis (4-6 m at MHWS), extending from Hobsonville to the junction of the Rangitopuni and Brighams Creeks, from which branch six shallow (2-4 m at MHWS), narrow tidal creeks of varying geometry and size (Fig. 2.1). The estuary deepens significantly at constrictions and waterway junctions, where flows increase, e.g. the mouths of the Paremoremo and Lucas Creeks (8-12 m at MHWS), adjacent to Herald Island (18 m at MHWS) and at the narrow throat between Hobsonville and Greenhithe (10 m at MHWS). Considerable areas of the harbour are less than 2 metres in depth at MHWS and are exposed as low gradient tidal flats at low tide (Plate 1.1). The intertidal flats are cut by narrow incised drainage channels that feed the central creek channels.

The estuary receives drainage from a catchment of 200 km^2 (Fig 1.1). Approximately 90% of the harbour's freshwater input enters at the headwaters of the Rangitopuni, Brighams, Paremoremo, Waiarohia and Lucas tidal arms. The Rangitopuni being the largest single freshwater source (Table 2.1). The summer and winter flows are small compared to the tidal prism, about 0.5% for summer flows (cf. Tables 2.1 and 2.2). Stream inflow increases markedly for short periods during floods (Smith 1983).

Tides are semi-diurnal with mean spring and neap ranges of approximately 3 and 2 metres respectively. Tidal currents show marked across channel variation but mid-channel velocities are in the order of 0.5 and 1 m/sec for neap and spring tides respectively. The tidal prism of the Upper Harbour comprises 73% and 55% of the high water volume for spring and neap tides respectively (Table 2.2).

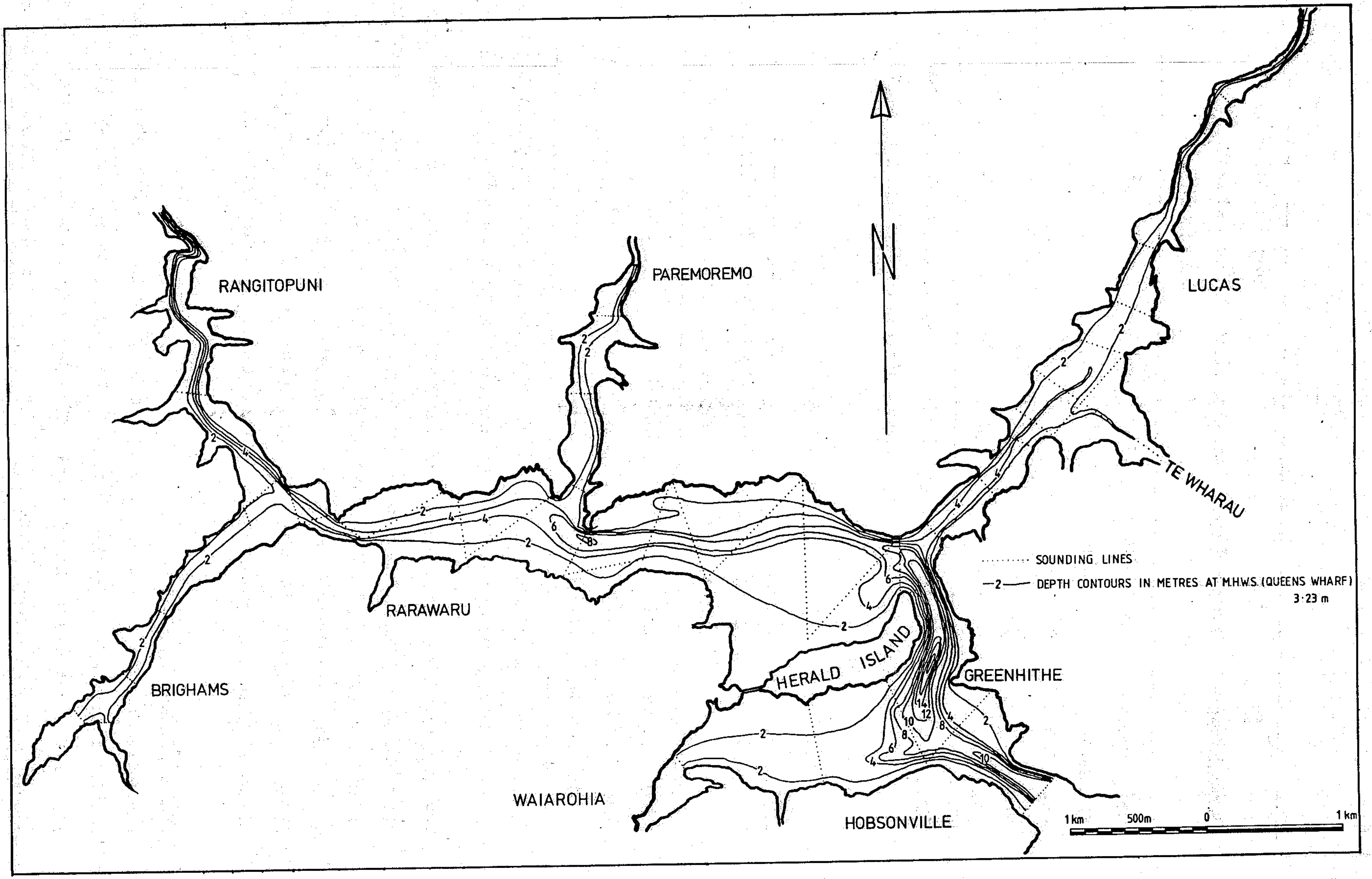

Fig. 2.1 : Bathymetry of the Upper Waitemata Harbour.

Subcatchment	Summer Flow	Winter Flow	Proportion of flow into headwaters of subestuary (%)
Rangitopuni	50 - 600	1100 - 6500	98
Brighams	40 - 200	200 - 800	85
Paremoremo	40 - 120	70 - 380	87
Lucas	30 - 210	340 - 1180	60
Waiarohia	20 - 100	50 - 200	80

Table 2.1 : Approximate mean daily flows (litres/sec)for the Upper Waitemata subcatchments (from Williams and Rutherford 1983).

	Spring Tides (Range 3.6 m)	Average Tides (Range 2.5 m)	Neap Tides (Range 2.0 m)
H.W. volume	25600	22000	18300
L.W. volume	7000	8000	8300
Tidal Prism	18600	14000	10000

Table 2.2 : Tidal volumes (x 1000 m^3) in the Upper Waitemata Harbour (after Williams and Rutherford 1983).

The strong tidal influence and elongate nature of the system means circulation largely parallels the major channel systems. Exceptions occur in the shallow water area north of Herald Island where anticlockwise rotatory circulation appears to be generated on flood flows. A variety of minor water movements occur, particularly over shallow intertidal areas, due to wind generated currents and waves.

2.2 DEPOSITIONAL HISTORY

The present distribution pattern of continental shelf marine sediments of the Hauraki Gulf began to form during the latter part of the Otiran (or last) glaciation about 20000 yr BP (years before present, where present = 1950) when sea level stood about 130 metres below its present level. At that time the ancestral shoreline probably lay east of its present position and between the present 100 and 125 m isobaths. During this time the ancestral Waitemata River extended from its headwaters near Rewiti and Waimauku to meet the sea, on what is now the continental shelf, near Great Barrier (Gregory and Thompson 1973). Drill hole records and seismic profiling in the Waitemata Harbour show the ancient topography through which the river flowed to be very irregular perhaps with precipitous buried slopes comparable to those cliffs and steep-walled valleys that can be seen about the harbour shores today (Hicks and Kibblewhite 1976).

It is generally accepted that from 15000 to 20000 years ago, there was a rapid perhaps oscillatory, (Curray 1965, Cullen 1967) rise in sea level (averaging 8 mm/yr) until about 7000 yr BP, when sea level was approximately 10 metres below its present level.

Subsequent changes are more debateable showing a generally smooth (e.g. Shepard 1963) or an oscillatory (Morner 1969) slowing down (1.4 mm/yr) in rise until the present. Fairbridge (1961) and Schofield (1973, 1975) suggest a rapid rise in sea level to 2 to 3 metres above existing sea level by 6000 yr BP, followed by periodic high sea levels until 4000 yr BP, which were followed by fluctuations nearer present sea level to the present day.

Radiocarbon dates of shallow water estuarine fauna from Hellyers Creek cores (Hellyers Core 4, Figs. 2.2 and 2.3) show that marine sedimentation 1.0 km upstream from the entrance began by 6460 yr BP. Similar fauna dated from Lucas Creek cores (Lucas Core 10; Fig. 2.4 and 2.5) demonstrate that sedimentation was already taking place 1.7 km upstream of the entrance in the Te Wharau area by 5730 yr BP, i.e. sediment deeper than 0.4 metres below the bed of the blind channel on L14 (Figs. 2.5 and 2.6) were laid down before 5730 yr BP. Perhaps much of the sediment below this level across L14, and the many metres of thick sediment in the Lucas Creek entrance reach (L15 - L18, Figs. 2.6 and 2.7) were laid down before 6000 yr BP. Comparison with sea level curves for the period (e.g. Curray 1965; Cullen 1967, 1970) and the level of basement and recent estuarine sediments suggests sedimentation probably occurred between 9000-6000 yr BP and perhaps very rapidly as sea level rose abruptly. Hence only the top few

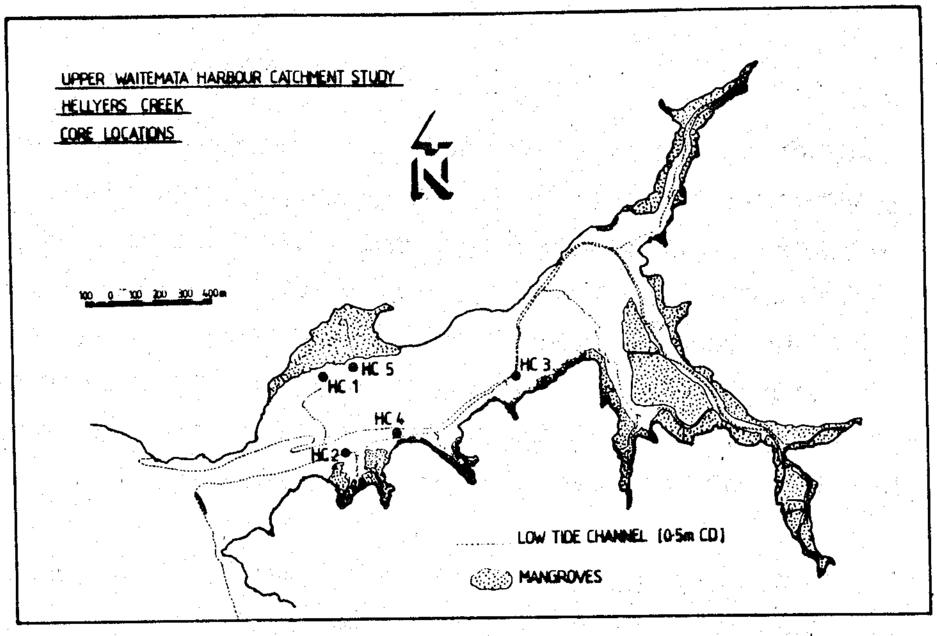

Figure 2.2 : Locations of core samples in Hellyers Creek.

metres will represent deposits less than 6000 yr BP in age.

Radiocarbon dates from the Hellyers Core 4 (Fig. 2.3) record that the sedimentation rate doubled over the more recent 1070 yr BP - present period compared to the earlier 6460 - 1070 yr BP period, possibly as a result of catchment use change.

Changes in catchment use are only recorded clearly where the sediment column is thickest. In the upper one metre of the ten metre thick sequence at Lucas Core 12 (Figs. 2.4 and 2.8), the pollen distribution records changes in catchment vegetation (Fig. 2.9) that equate with firstly the arrival of Polynesian and then, more recently, the European settlers (Fig. 2.10).

The pollen show that when the Maori first came to the Waitemata in about 1420 AD (530 yr BP) he would have viewed forest areas dominated by rimu, podocarp, rata, kauri, beech and toatoa. He practiced small scale burning of areas on the isthmus and upper harbour to obtain or cultivate food (Schriven 1981), a practice that would prevent forest regeneration and cause an increase in secondary growth such as bracken (Fig. 2.10).

It was 1840 AD (110 yr BP) before the European undertook significant

Core Description : Hellyers 4

Hellyers 4

0 - 6 cm	Olive brown sandy silt. Diffuse irregular boundary.
6 - 12 cm	Brownish black slightly mottled sandy silt common bivalve debris, traces fibrous carbonaceous material. Diffuse irregular boundary.
12 - 29 cm	Grey sandy silt. Rare bivalve debris traces fibrous carbonaceous material. Diffuse irregular boundary.
29 - 35 cm	Grey sandy silt, common bivalve debris. Trace fibrous carbonaceous material. Sharp irregular boundary. [^{14}C].
35 - 40 cm	Grey fine sand, abundant bivalves both whole and debris. Trace fibrous carbonaceous material. Sharp irregular boundary [^{14}C].
40 - 103 cm	Grey green mud with rare flecks of fibrous carbonaceous material and calcareous material throughout. Boundary diffuse regular.
103 - 104.5 cm	Grey-green slightly sandy mud with few shell debris. Boundary diffuse regular.
104.5 - 109 cm	Grey-green mud with rare carbonaceous flecks throughout. Diffuse regular boundary.
109 - 111 cm	Green-grey slightly sandy mud with few bivalve debris. Boundary diffuse regular.
111 - 125 cm	Grey green mud. Boundary irregular diffuse.
125 - 130 cm	Grey fine sand with abundant bivalves both whole and debris. Boundary irregular sharp [^{14}C].
130 - cm	Basement

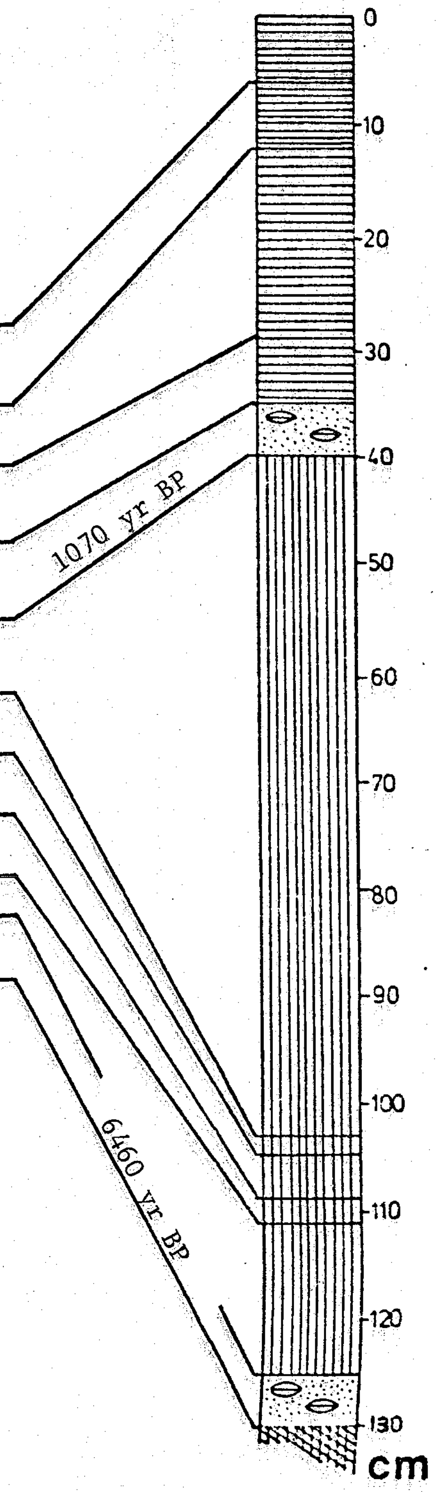

Figure 2.3 : Core 4 from Hellyers Creek (Fig. 2.2) showing two shell layers from which _Chione_ were dated by radiocarbon methods.

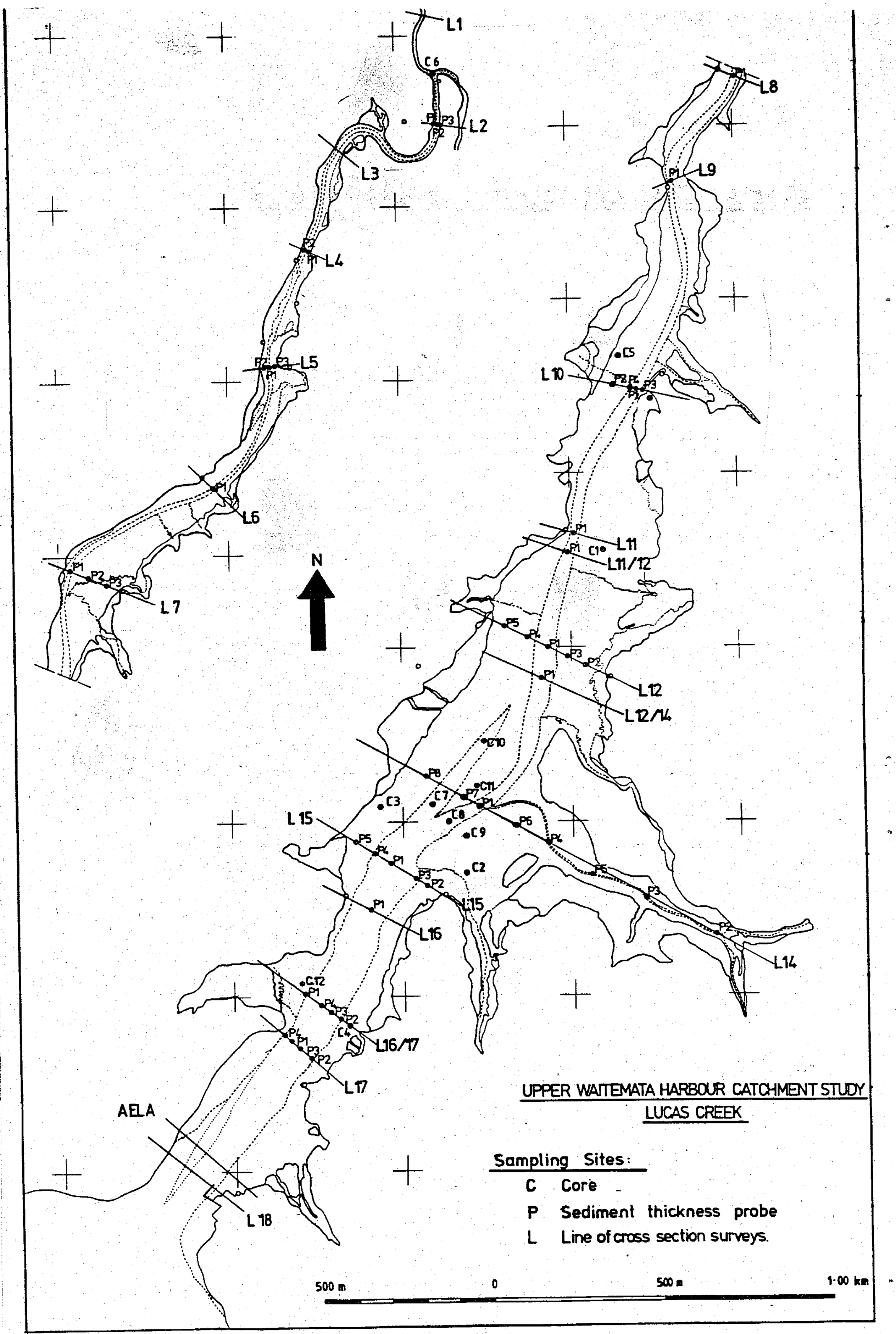

Figure 2.4 : Locations of surveyed channel cross sections, sediment thickness probes and core samples in Lucas Creek. The dotted line defines the low tide channel and the fine line, mangrove communities.

Core Description: Lucas 10

Lucas 10

0 - 3 cm	Olive brown silt, mottled. Sharp regular boundary.
3 - 30 cm	Olive brown with black, mottled silt. Traces fibrous carbonaceous material. Sharp regular boundary.
30 - 33 cm	Brown grey silty sand with black mottles. Rare bivalve debris, rare fibrous organic material disseminated throughout. Sharp regular boundary.
33 - 46 cm	Brown grey silty sand, abundant bivalves both whole and debris. Pieces of fibrous carbonaceous material disseminated throughout. Fibrous carbonaceous layers at 36, 40 and 42 cm. Sharp regular boundary. [^{14}C].
46 - 55 cm	Grey silt, Rare organic and calcareous matter disseminated throughout. Sharp regular boundary.
55 - 87 - cm	Grey silt, Rare fibrous organic material disseminated throughout. Few bivalves, mostly whole.

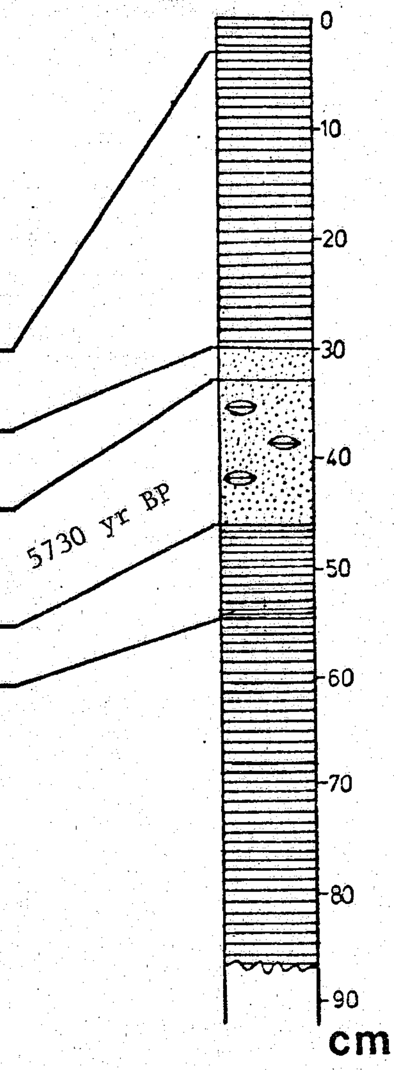

Figure 2.5 : Core 10 from Lucas Creek (Fig. 2.4) showing a shell layer from which *Chione* were radiocarbon dated.

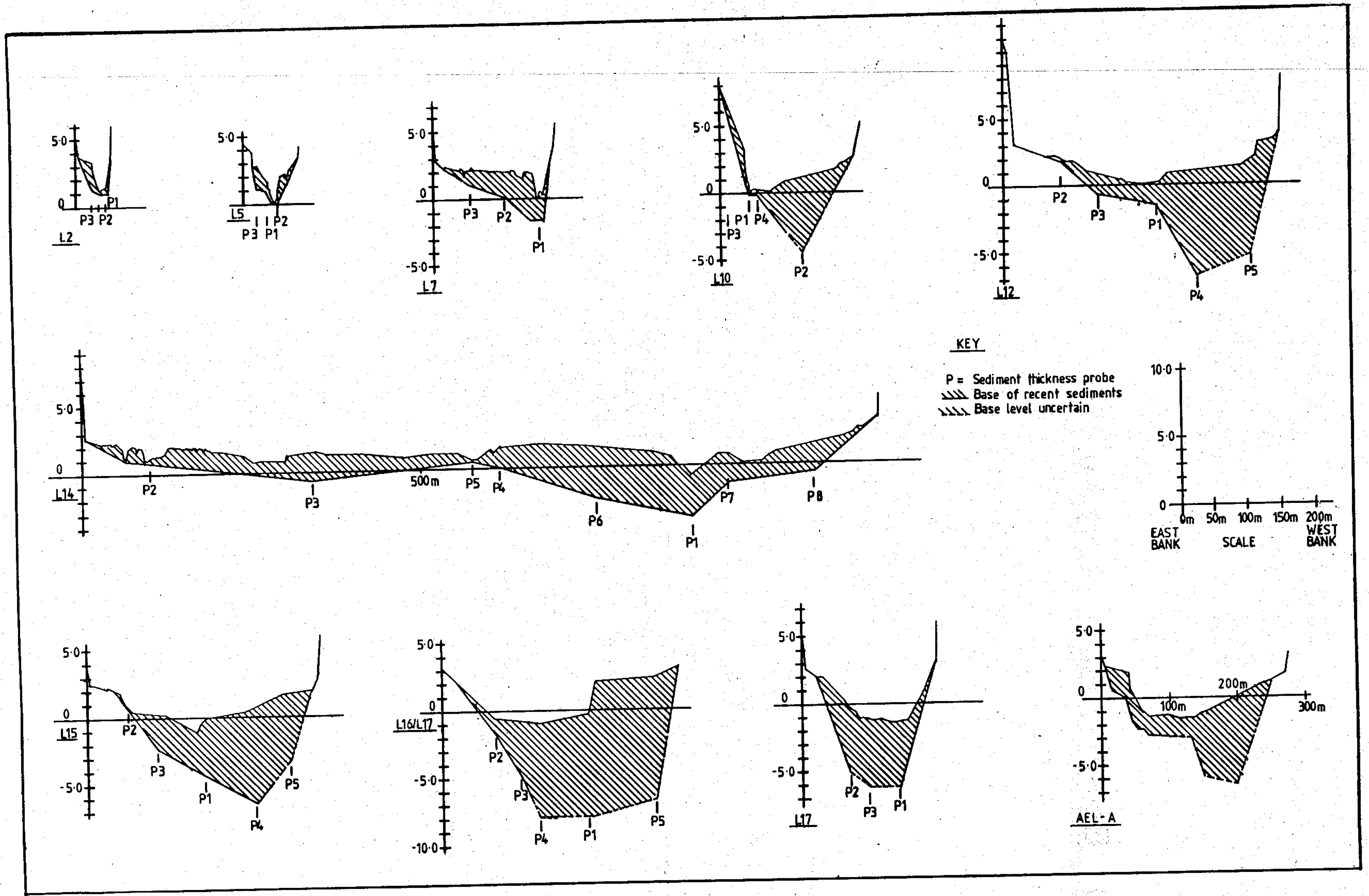

Figure 2.6 : Thickness of unconsolidated recent sediments in Lucas Creek determined by probing sediments with steel rods at selected locations (Fig. 2.4). Note that the present day channel does not always coincide with the palaeochannel e.g. at L10. Survey made in April 1980.

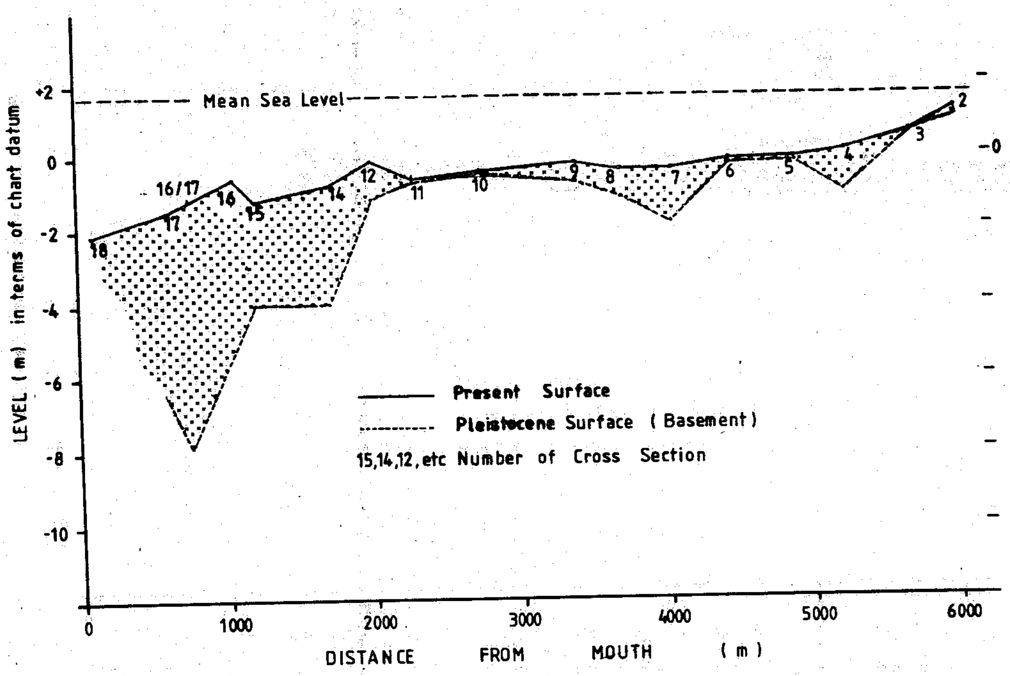

Figure 2.7 : Longitudinal profile of bed level and sediment thickness in Lucas Creek.

investigations of the upper harbour, and 1841 AD when large blocks of land were purchased from the Maoris (Schriven 1981). Timber milling operations began as early as 1841 AD,and along with gum digging proceeded rapidly. The decimation of remaining forest by fire and timber haulage, the modification of stream banks to straighten the line of flow to assist log transport, and pit digging associated with kauri gum exploitation, would have resulted in increased erosion and dissection and increased sedimentation, at least until a new vegetation cover could establish itself. It is difficult to establish when forest clearance finished in the Upper Waitemata Harbour catchment, but it was nearly 1870 AD before farming became significant (Schriven 1981, p.5). The catchment use changes brought about by the European are reflected both in the pollen spectra of the sediments and perhaps in the four-fold increase in sedimentation rate (Fig. 2.10).

In other parts of the estuary where the sediment is thinner (e.g. Hellyers Creek Cores 1 and 5, Fig. 2.2; Lucas Creek Core 3, Fig. 2.4) the changes over the last 1000 years are compressed and blurred in the upper 10 cm or so of sediment. In other words, the estuary has

Core Description : Lucas 12

Lucas 12

0 - 6 cm	Brownish olive mud. Fibrous carbonaceous material at surface. Boundary diffuse irregular.
6 - 89 cm	Green grey mud. Rare bivalves both whole and debris. Trace flecks and pieces fibrous organic matter disseminated throughout. Boundary sharp regular.
89 - 93 cm	Green grey mud, Trace flecks and pieces fibrous carbonaceous material disseminated throughout. Abundant bivalves both whole and debris. Boundary sharp regular.
93 - 110 - cm	Green grey mud. Rare bivalves both whole and debris. Trace flecks and pieces fibrous carbonaceous material disseminated throughout.

NOTE: Samples for Pollen Analysis Taken in 1 cm bands.

0-1, 4-5, 9-10, 14-15, 19-20, 24-25, 29-30, 34-35, 39-40, 44-45, 49-50, 59-60, 69-70, 79-80, 89-90, 99-100

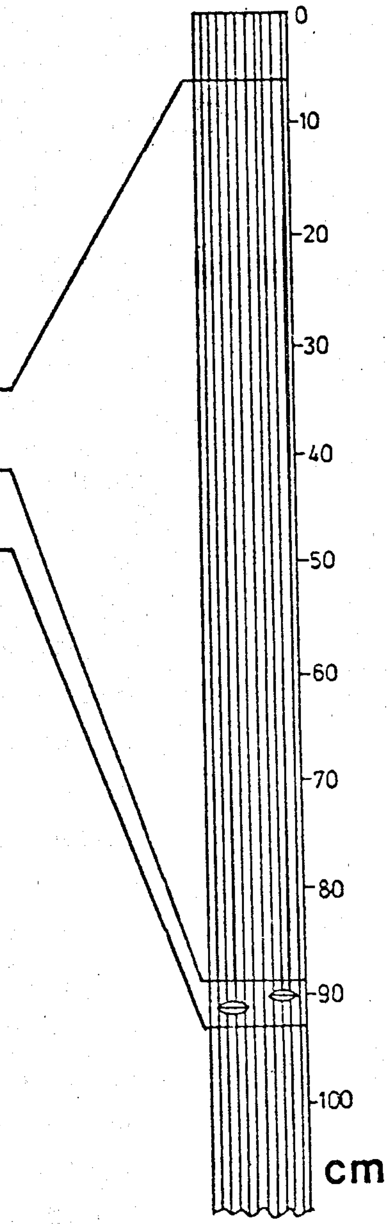

Figure 2.8 : Core 12 taken near the entrance to Lucas Creek (Fig. 2.4) from which pollen were counted. The sediment column at this location is over 10 metres thick.

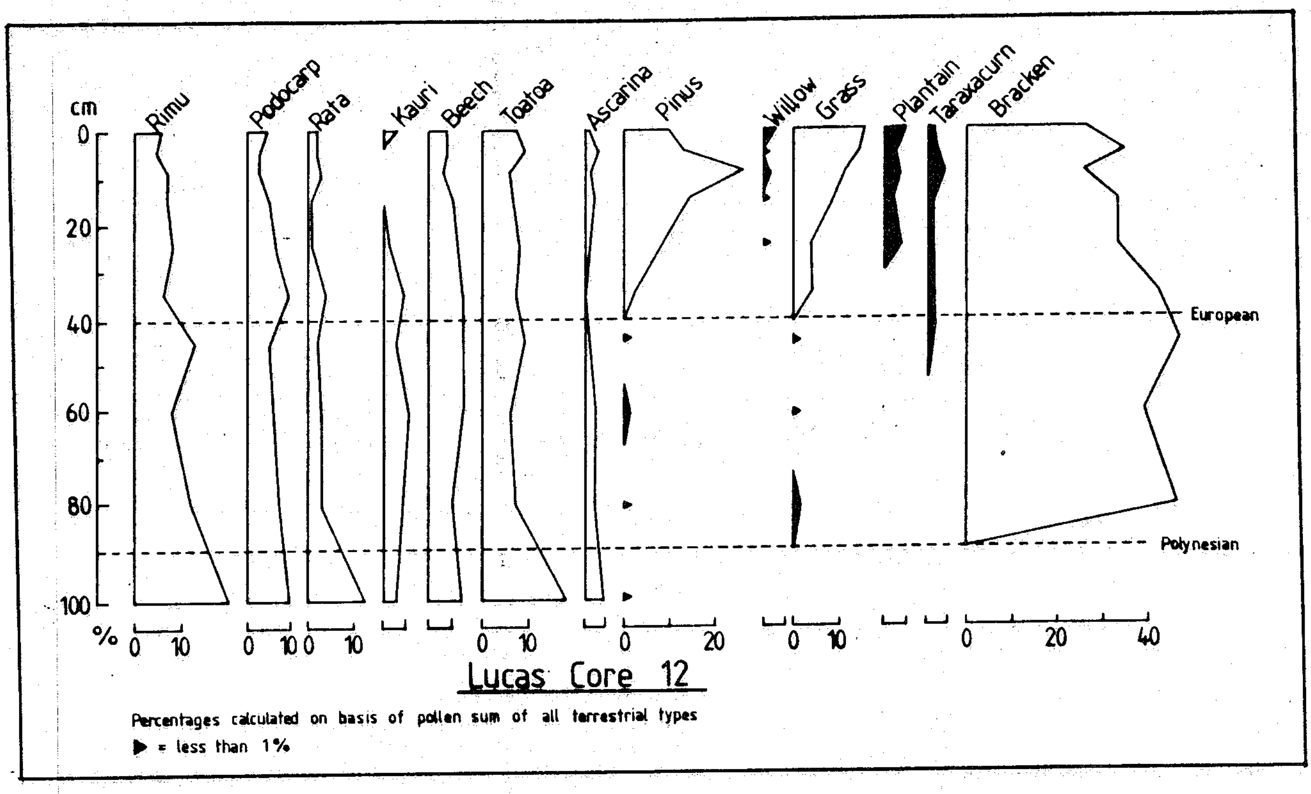

Figure 2.9 : Pollen distribution in Lucas Core 12 (Fig. 2.8). Percentages calculated on the basis of pollen sum of all terrestrial types. Pollen counts by M. McGlone. The trace amounts of <u>Pinus</u> and Grass lower in the core probably result from mixing during corer penetration.

reworked much of the input material and flushed it from the system despite the large increase in sediment input responsible for a four-fold increase in sedimentation rate recorded in the sediment column in some parts of the system. In the central and channel area of Lucas Creek there has been zero sedimentation or net erosion over the last 125 years (1854 - 1979 AD) (Fig. 2.11).

The numerous volcanic cones and craters that mark the Auckland landscape testify to intermittent volcanic activity on the Auckland isthmus since about 40000 yr BP (Searle 1964, 1965). Even though eruptions continued over the more recent period when upper Waitemata Harbour sediments were being deposited, none of the Lucas or Hellyers Creek cores showed evidence for eruptions in the form of layers of volcanic material. This could in large part be due to the fact that the amount of airfall material (lapilli, scoria and ash) erupted from

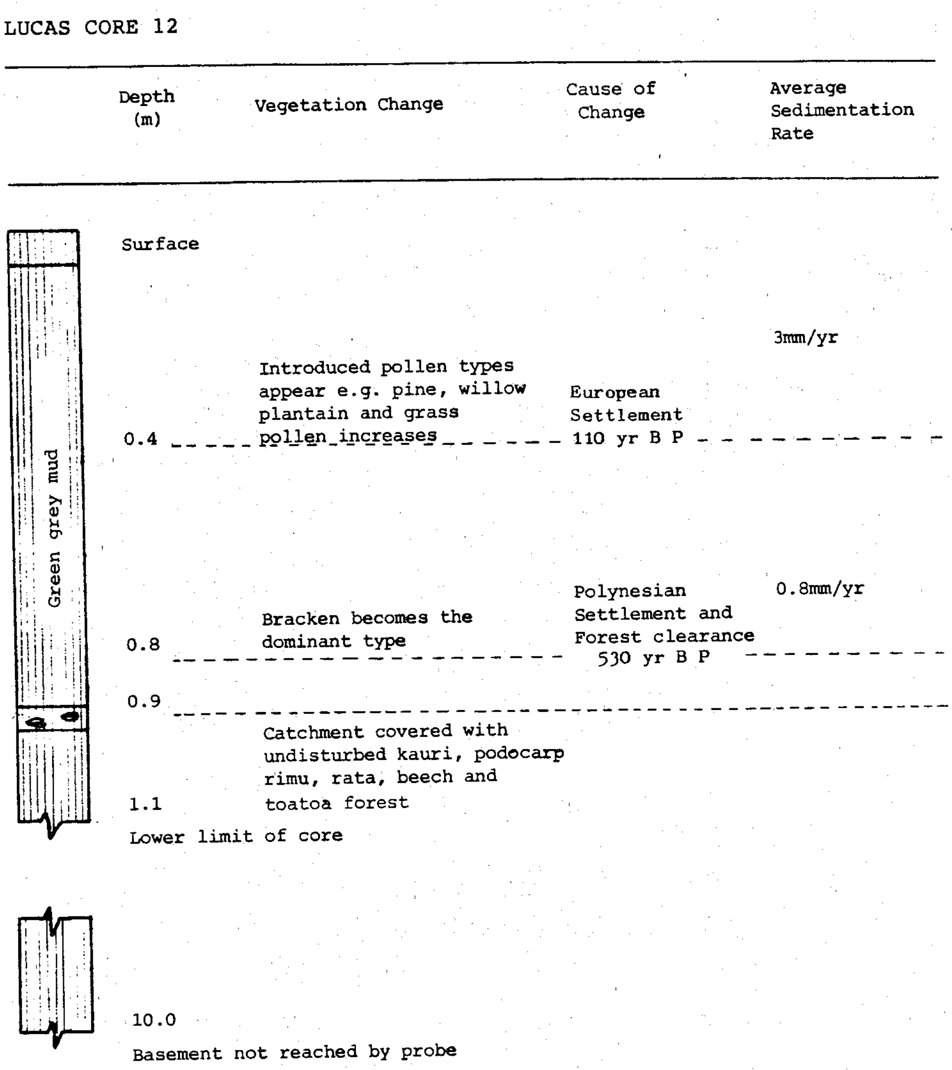

Figure 2.10 : Lucas core 12 sampled near the entrance to Lucas Creek (Fig. 2.4). Pollen distribution in sediment is related to catchment use change and sedimentation rates are derived.

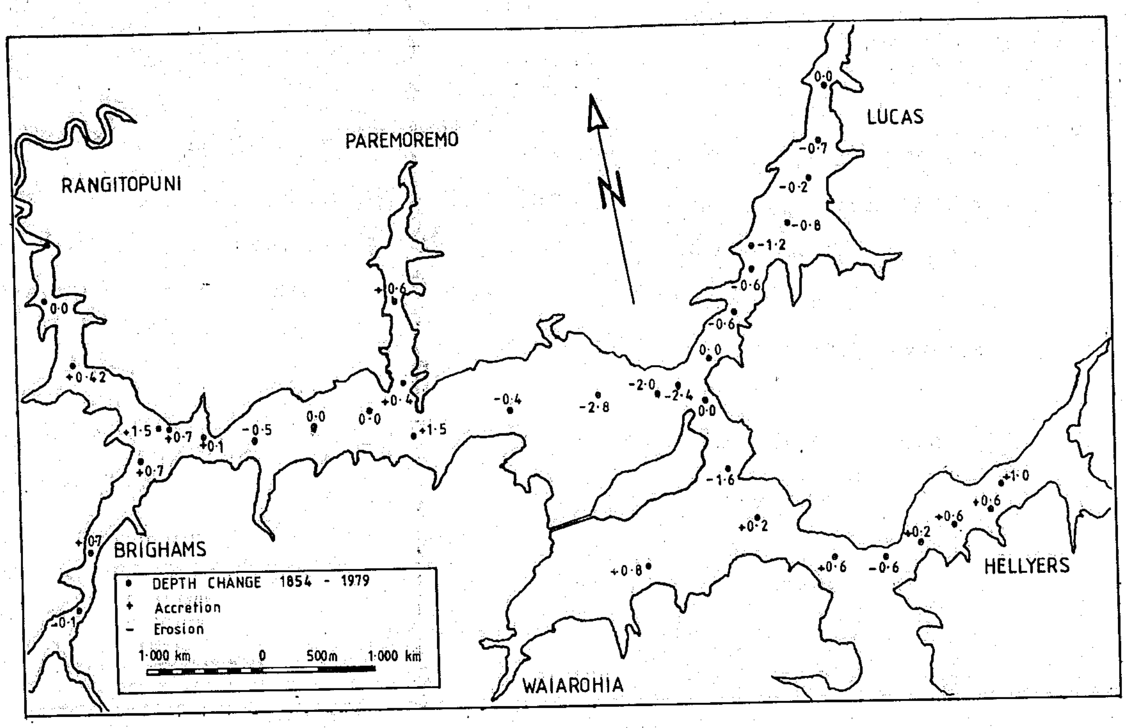

Figure 2.11 : Net sedimentation in the Upper Waitemata Harbour between 1854 and 1979 based on comparison of soundings made in 1854 (British Admiralty 1854) and 1979 (Johnston 1980). Error range in soundings resulting from datum determination, depth measurement method and position fixing are probably in the order of 0.7 m for the 1854 and 0.3 m for the 1979 data.

the individual centres was small and/or that tidal and biogenic reworking redistributed volcanogenic debris.

By 1854 AD, when the HMS Pandora surveys were made, catchment clearance by the European was well under way (Schriven 1981) and much of the estuarine sedimentation due to logging in the catchment may have taken place. Comparison of the 1854 and 1979 soundings indicate that the mid and lower reaches of the tidal creeks (with the exception of Lucas Creek) have seen net deposition in this period (possibly largely as a function of sediment generated in the later phase of forest clearance by the European), while the main axis has shown varying amounts of erosion and deposition (Fig. 2.11). This could mean that in future times the middle and lower reaches of the tidal creeks will be the most likely sites for sediment accumulation while high fresh water influx accompanying floods will inhibit deposition in the upper reaches.

The net erosion in the channel area of Lucas Creek over the last 125 years (Fig. 2.11) is an interesting feature and may indicate that sedimentation accompanying early European bush clearances was over prior to the 1854 HMS Pandora survey or that Lucas Creek has a far greater flushing capacity than the other tidal creeks.

In very recent times mans activities are represented in sediment distribution patterns : (1) to the south of Herald Island where bathymetric data (Fig. 2.11) and local opinion point to a build-up of sediment since the construction of the Herald Island causeway cut off tidal flow from behind the island, and (2) adjacent to the southern shores of the Hellyers Creek estuary, where sediment accumulation is perhaps due to urbanisation of its catchment (Fig. 2.12).

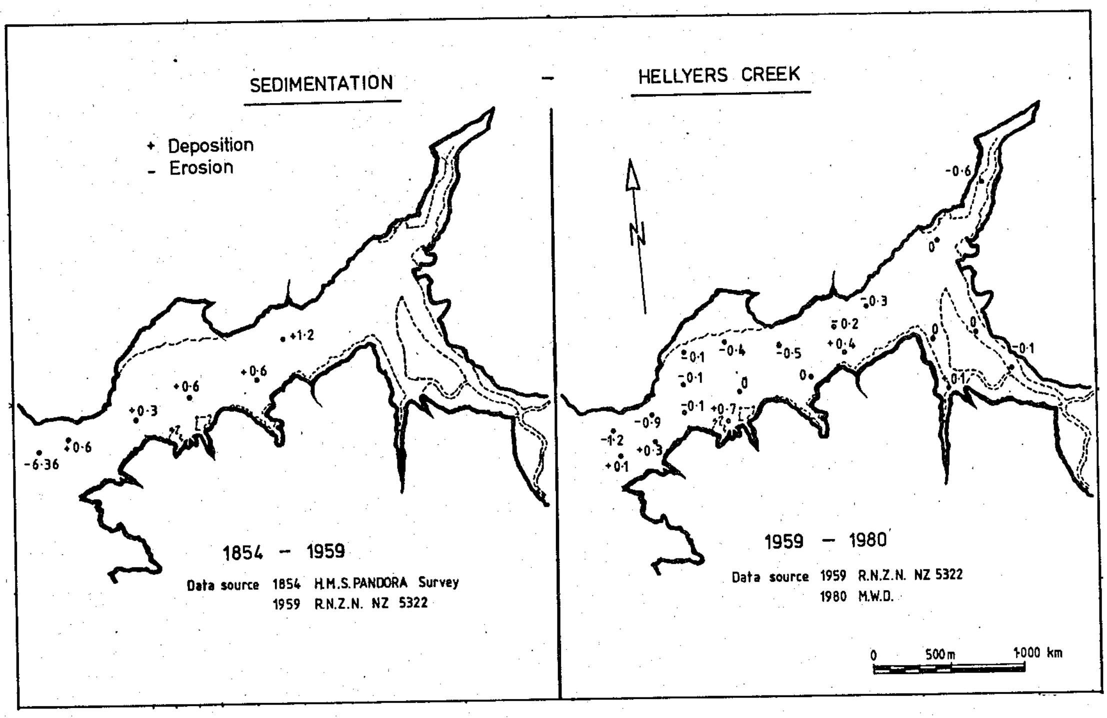

Figure 2.12 : Net sedimentation in Hellyers Creek over the periods 1854 (British Admiralty 1854) and 1959 (RNZN Hydrographic Office 1959) and 1959 to 1980 (survey by MWD). Error range in soundings is probably in the order of 0.3 m for the 1980 data.

The stability of the channel and tidal flat areas over historical times is more difficult to assess. Sediment cores from Lucas and Hellyers Creeks show changing lithologies at some sites (e.g. Figs. 2.3 and 2.5) that could be due to either lateral channel migration and associated change in depositional environment, or catchment condition change. The thickness of recent unconsolidated marine sediments in Lucas Creek at L10, L12, L15, L16/L17 and AELA (Fig. 2.6) show that the existing channel does not coincide with the channel bed cut into basement material (i.e. the original stream before drowning by rising sea level) and that the palaeo channel lay closer to the western bank indicating lateral channel migration of over 100 metres since sedimentation began some 6000 years ago. Air photographs that back date some 30-40 years do not show significant changes in channel position. It is likely that the gentle channel curves found in the tidal creeks migrate slowly downstream but that the changes have been in the order of hundreds of years in time.

2.3 SEDIMENT SOURCES

Sediment input derives primarily from the streams that discharge into the headwaters of the Upper Waitemata Harbours 6 tidal arms (Fig. 2.1). Unfortunately, sediment input data is available for suspended loads only. Without bed load data, total sediment input must be considered as a conservative estimate. However, several factors suggest the bulk of sediment input is suspended load; (1) the bulk of surficial sediments are of a particle size that are normally transported in suspension, (2) there is no trend of increasing particle size towards the points where streams enter the estuary - locations where bed load size material would be expected to be deposited, and (3) the bulk of the catchment erosion products are of a fine grain size and capable of being carried in suspension (Jessen 1983).

Estimates of the total suspended solids input for the major contributing sources to the Upper Waitemata Harbour estuary are listed in Table 2.3 (after van Roon 1983). The data were determined by sampling stream surface waters, laboratory analysis to determine suspended solids (non-filterable residue) concentration, derivation of a stream stage height/suspended solids relationship (sediment rating), and application of this relationship to the stream discharge/time-hydrograph to give total daily mass transport of suspended solids. Because the samples are surface samples, the sediment ratings are of variable quality, and various assumptions are made in calculating the total loads, the data should be considered to be best estimates only. For a complete description of the data and assumptions made in their calculation refer to van Roon (1983).

Annual inputs for 1980 (Table 2.3) show that the Rangitopuni (61%) and Lucas Creek (14%) estuaries are the most important sources of suspended solids to the Upper Waitemata Harbour. It is significant that the largest input of approximately 12707 tonnes, contributed by the Rangitopuni, enters the estuary head where flushing is poorest.

Total input load for 1980 and 1981 for the major sediment contributor, the Rangitopuni, reveals some interesting features. In 1980 the mean yield was 35 tonnes/day, the total yield was 12638 tonnes/year, of which 65% was contributed on 15 March 1980 (Cyclone Sina) and 89% was contributed in 7 flow days (or 2% of the flow duration time). In 1981 the mean yield was 9 tonnes/day, the total yield 3187 tonnes/year of which 11% was contributed on 2 September 1981 and 36% was contributed in 7 flow days. The 1980 sediment yield is 4 times that of 1981 primarily due to one large storm.

It is apparent that sediment discharge to the estuary varies markedly from year to year as a function of the size and frequency of storm events, and that a large proportion of sediment inflow occurs over a small period of flow duration.

2.4 SURFICIAL SEDIMENTS

Surficial sediments have been described by Thompson and Gregory (1973), Fry and Hume (1980), and Bioresearches Limited (1981). Surficial sediment texture is shown in Figure 2.13 and is based on Bioresearches (1981). Details of sampling methods and analysis are given in Bioresearches (1981).

	Catchment Area (km^2)	Suspended Solids			
		1980		Year 2000	
		tonnes/yr	%	tonnes/yr	%
Rangitopuni					
Riverhead Sewage	-	-	-	31	0.1
Rangitopuni at Walkers	81.5	12632	60.9	12632	45.3
Deacon Forest	3.6	75	0.4	1533	5.5
Brighams					
Ngongetepara	11.2	107	0.5	107	0.4
Totara Creek	5.7	556	2.7	893	3.2
Thomas Richards	-	0.3	<0.1	<1	<0.1
Rarawaru	2.2	90	0.4	90	0.3
Waiarohia	3.8	156	0.8	156	0.6
Paremoremo					
Sewage	-	5.5	<0.1	11	<0.1
Catchment	7.4	700	3.4	700	2.5
Lucas					
Lucas at Gills Rd	6.3	900	4.3	974	3.5
Oteha at Days	12.1	1947	9.4	5724	20.5
Albany Meats	-	0.4	<0.1	-	-
Albany Hotel	3.1	0.1	<0.1	-	-
Balance of Catchment					
Hobsonville Sewage	-	5	<0.1	10	<0.1
Whenuapai Sewage	-	7	<0.1	14	<0.1
Septic Tanks	-	24	0.1	29	0.1
Papanui Farms	-	0.6	<0.1	<1	<0.1
Balance of Catchment	51.0	3544	17.1	4954	17.8
Total		20750		27860	

Table 2.3 : Annual inputs of suspended solids (non-filterable residue) to the Upper Waitemata Harbour from the major subcatchments (from van Roon 1983). Inputs from outside the subcatchment measurement station areas are included in Balance of Catchment. Year 2000 estimates are described in van Roon (1983).

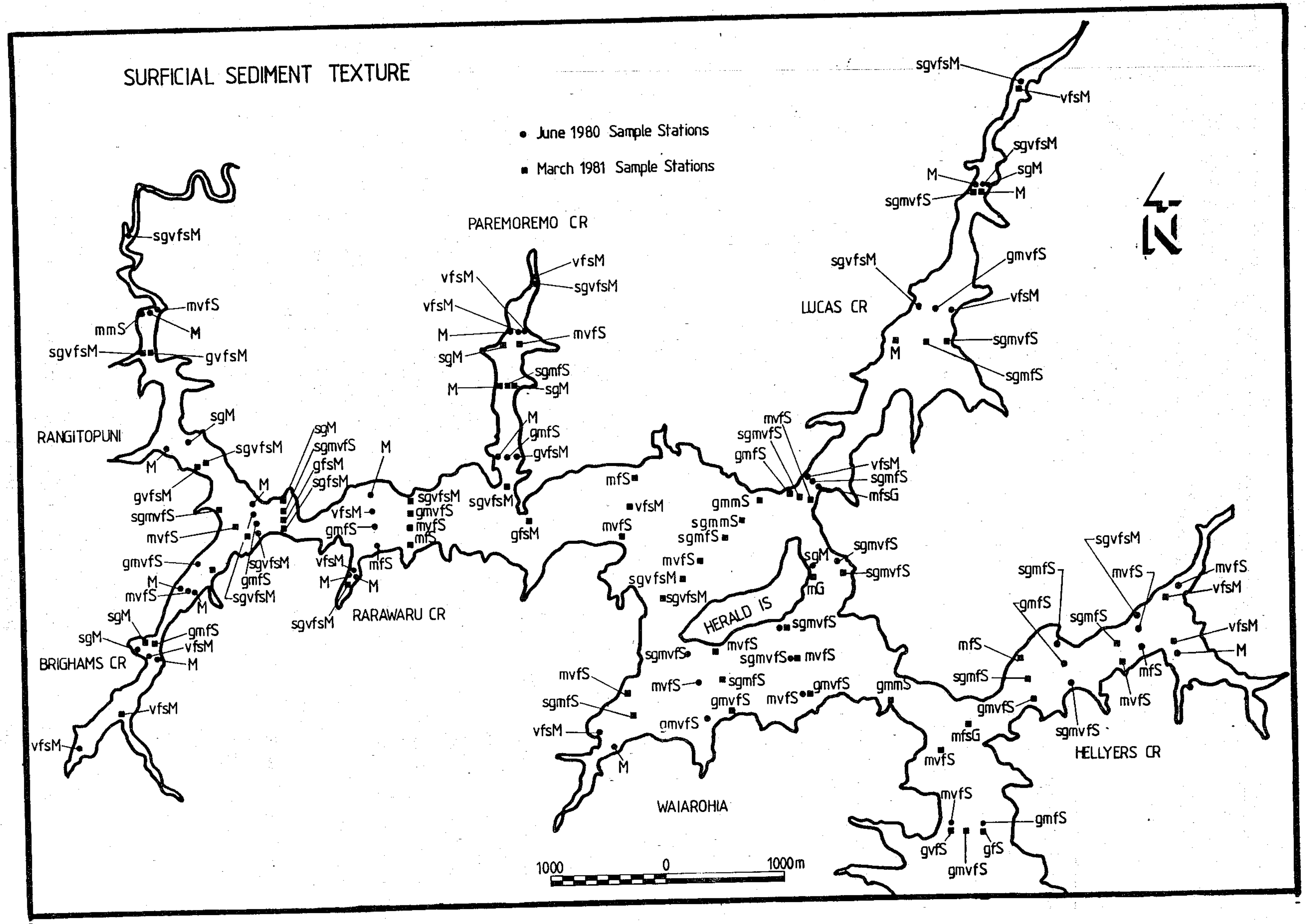

Figure 2.13 : Upper Waitemata Harbour surficial sediment texture (after Bioresearches 1981). Textural terms are defined in Appendices I & II.

Although large areas of intertidal flats are exposed at low water direct examination of sediments is made difficult by low water clarity, and soft muddy sediments that make foot access extremely difficult. Sediments are generally fine grained being largely sandy muds and muddy fine sands (Fig. 2.13 and Appendix II). Texture is closely related to environmental energy. The coarsest sediments, which include gravelly fine sands, medium sands and gravels, represent the areas of highest energy and are located along the main harbour axis from Lucas Creek south, particularly in the deep channel section adjacent to Herald Island, and the creek entrances. Most of the gravel size material in samples is shell debris. Mud is absent where gravel lag deposits concentrate in areas swept by strong tidal currents. In or near the main axis and tidal creek channels the sediments are dominated by muddy and gravelly very fine sands, areas of environmental energy lower than those above. Muddy very fine sands and sandy muds occur in the tidal flat areas, largely in the arms of the tidal creeks, where environmental energy is low. The finest sediments predominate in the mangrove and embayed areas where deposition takes place at the upper level the tide reaches, where current velocities are minimal and shelter from wave and tidal flow is good, and in creeks such as Brighams and Rarawaru where environmental energy is low.

Locally, wave action concentrates sand size material at several more exposed locations in the main axis, to form sandy beaches that constitute an important recreational resource (Duncan 1981).

Present day sedimentation rates are difficult to quantify because sediment accumulation in muds is very slow, varies in rate from place to place, and is difficult to physically measure. A rough estimate of the maximum possible average sedimentation rate for the upper harbour can be calculated for 1980, a year in which rainfall was approximately 9% less than the 40-yr normal annual rainfall (Smith 1983). If all the 20750 tonnes (Table 2.3) transported to the estuary was deposited it would have a volume of :

$$\frac{20752 \times 1000 \text{ kg}}{1100 \text{ kg/m}^3} = 18865 \text{ m}^3$$

where 1100 kg/m^3 is the density of surficial sediment (see Section 1.4). If the sediment were spread evenly over the bed of the estuary it would form a layer :

$$\frac{18865 \text{ m}^3}{741 \times 10000 \text{ m}^2} \quad = \quad 0.003 \text{ m thick}$$

In other words the net sedimentation rate would be in the order of 3 mm/annum. This would increase slightly if bed load were included. The sediment would be deposited at different thickness in different places according to local environmental energy. Although the 3 mm/annum is an average maximum value, as some of the input sediment must pass directly through the system and to the Waitemata Harbour or the Hauraki Gulf, it is in line with the 3 mm/yr rate obtained from pollen data (Fig. 2.10) and similar to the 2.9 mm/yr measured in the Pauatahanui Inlet (Pickrill 1979).

Storm events inject large proportions of the annual load into the system. Because of this, estuarine sediment deposition will occur in short periods of time, and net sedimentation rates will vary markedly from year to year.

The flushing characteristics of the Upper Harbour and individual creeks (Williams and Rutherford 1983) give a guide to the minimum time it takes to flush suspended sediment from the system (the actual residence time of sediment in the system would in fact be longer; sediment does not behave like a solute but may be deposited and resuspended). For average tides and low freshwater inflow, fine material injected at high tide (and that remains continuously suspended) could be flushed from Lucas Creek in 8-10 tidal cycles and from the upper harbour in 9-11 tidal cycles. During storm events high freshwater inflows are observed to push suspended solids laden waters well down the tidal arms and into the main axis, so flushing time would be shortened.

2.5 SEDIMENT NUTRIENTS

Nutrient levels in Upper Waitemata Harbour surficial sediments were examined by Fry and Hume (1980) and Bioresearches Limited (1981) (Fig.

2.14). Fry and Hume (1983) detail nutrient distribution in Lucas and Hellyers creek sediments and discuss changes in nutrients with season and depositional environment. Methods of sediment sampling and analysis differ between studies therefore comparison of results should be made with caution.

In Upper Waitemata Harbour surficial sediments total organic carbon (TOC) ranged between 0.4% and 5.1% with a mean of 2.08%, and total Kjeldahl nitrogen (TKN) ranged from 400 to 2700 mg/kg with a mean of 1300 mg/kg (Bioresearches Ltd 1982). Total phosphorus values range from 200 to 590 mg/kg with a mean of 363 mg/kg (Fry and Hume 1980, 1983).

Examination of the spatial distribution of nutrients show no clear trend down the axes of the tidal creeks. However, on an estuary-wide basis, TOC, TP and TKN values showed higher levels in the Rangitopuni, Brighams, Rarawaru and Paremoremo creeks than in the Lucas, Hellyers and Waiarohia inlets. TOC and TKN were higher in the western main axis than the east and lower in the channels than the tidal flats. The generally higher nutrients in the west relative to the east of the harbour coincides with poorer flushing and generally finer sediments in the west. The winter values (Fig. 2.14) are expected to rise even higher with significant natural seasonal (spring and summer) increases (see Section 3.5).

2.6 GEOMETRIC STABILITY

A number of workers, including O'Brien (1931), Furkert (1947), Bruun (1966) and Heath (1975), noted that for tidal embayments on sandy coastlines the relationship

$$A = CP^n$$

(where A is the entrance cross sectional area, P the tidal prism, and C and n are constants) indicates that the size of an entrance is one of the main factors determining the ability of flow to transport sediment through the entrance, and estuaries that conform to the relationship can be considered to be geometrically stable.

The major harbours in the Auckland area, the Manukau and Waitemata,

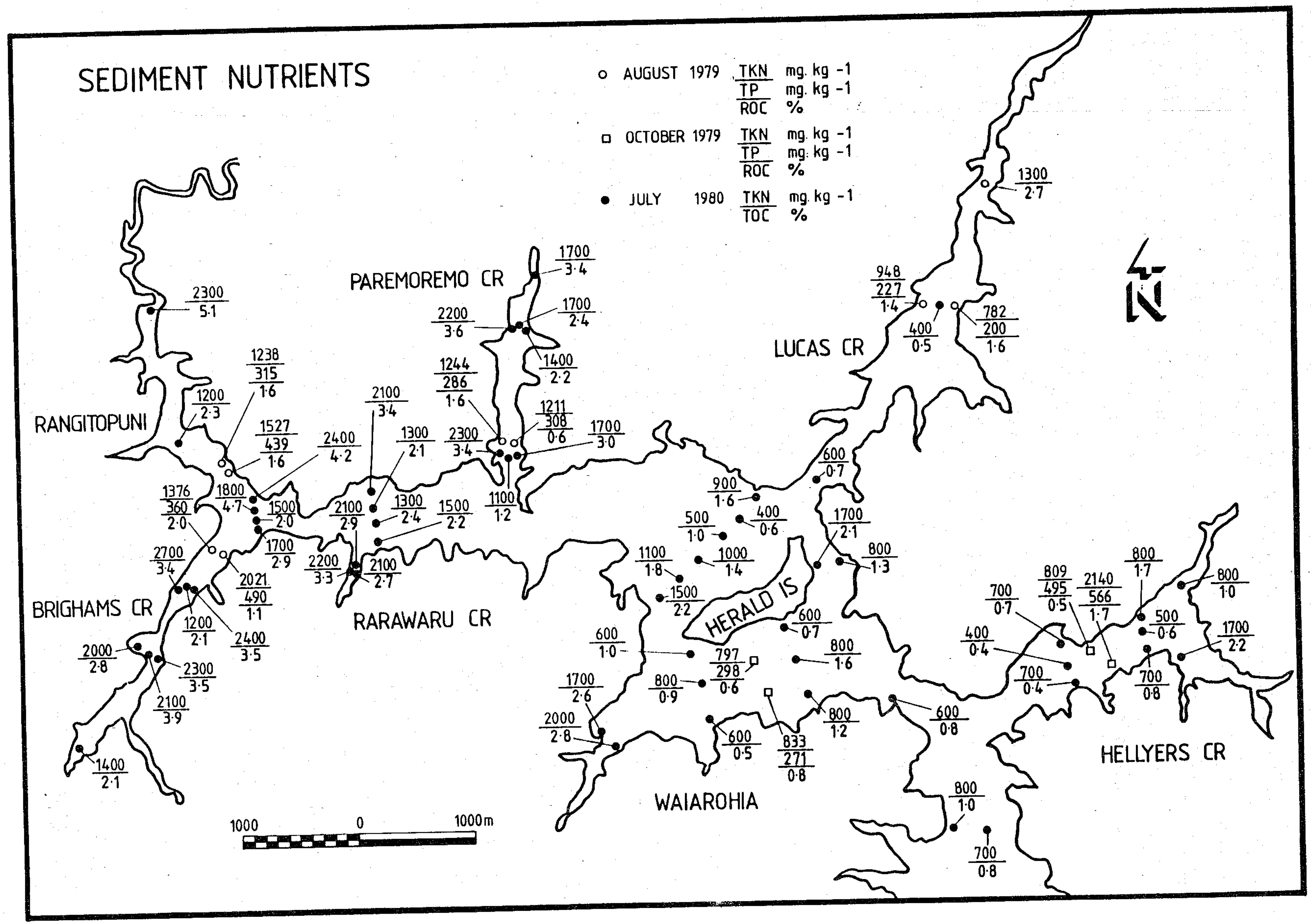

Figure 2.14 : Total kjeldahl nitrogen (TKN), total phosphorus (TP), total organic carbon (TOC) and readily oxidisable carbon (ROC) in Upper Waitemata Harbour surficial sediments. The August and October 1979 samples are described in Fry and Hume (1980) and the July 1980 samples in Bioresearches (1981). Further nutrient analyses of Lucas and Hellyers Creek sediments are detailed in Section 3.5.

have many similar hydrological and geomorphological features. They have constricted entrances to the outer oceanic waters that open to broad central regions floored with muddy sands and fringed with substantial areas of intertidal flats. These link with narrow tidal river arms floored with dominantly muddy sediments. An A-P relationship has been determined for the entrance cross sectional area A (below a tide level corresponding to peak discharge which is approxiately midway between mean tide level and mean high water spring) and tidal prism P (for a mean spring tide) for tidal waterways in the upper reaches of Auckland Harbours (Fig. 2.15 and Hume, in prep.) where :

$$A = 6.2 \times 10^{-3} \; . \; P^{0.76}$$

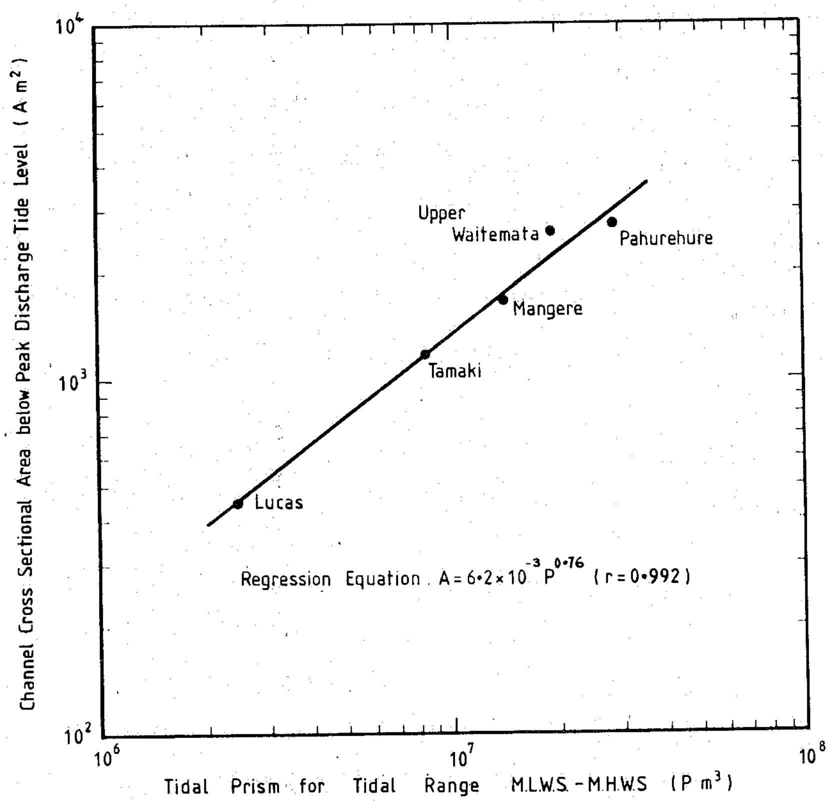

Figure 2.15 : Relationship between channel entrance cross sectional and spring tidal prism for tidal inlets in the Auckland area.

The relationship demonstrates that :

1 An A-P relationship analogous to that derived for open coast

sandy inlets and sandy tidal waterways holds for estuarine creeks floored with fine grained sediments.

2 Auckland inlets shown in Fig. 2.15 are in a state of net non-scouring, non-silting, sedimentary equilibrium.

In the absence of a more sophisticated model the relationship provides a semi-quantitative method for assessing the geometric stability of Auckland inlets.

Furthermore, it can be used to predict the changes in channel cross section resulting from dredging and reclamation of the intertidal area. For instance, if the tidal prism (P) is increased by dredging the estuary will accommodate this change, increasing the tidal throat cross sectional area (A) by scouring by an amount given by the above empirical equation.

The Upper Waitemata Harbour inlet lies to the left of the regression line indicating it is to some extent naturally unstable. Any such instability will be reduced by those events that cause an increase in the tidal prism (natural scour or dredging upstream of the entrance) and/or a decrease in the channel cross sectional area at Hobsonville (sedimentation or reclamation).

An <u>estimate</u> of the scale of change necessary to achieve inlet equilibrium for the upper harbour can be gauged from Fig. 2.15.

1 For the present mean spring tide compartment of 19.71×10^6 m^3, the existing entrance of 2340 m^2 cross sectional area below peak discharge level at Hobsonville should reduce to approximately 2240 m^2 to attain equilibrium. This could be achieved by natural sedimentation causing a reduction in cross section of approximately 4%.

2 Alternatively the tidal compartment, which is too small for the existing entrance, could be enlarged some 22% from 19.7×10^6 m^3 to 24.1×10^6 m^3. This would equate with natural erosion from the intertidal area of the whole part of the upper harbour estuary of 4.4×10^6 m^3 of sediment. Alternatively material

could be dredged from the intertidal area upstream of the entrance.

Because the two parameters covary it is most probable natural adjustments will occur in both simultaneously, rather than in just one alone.

While the derived A-P relationship (Fig. 2.15) is a simplification of complex processes it suggests Upper Harbour equilibrium would be encouraged by natural and engineering activities that promote erosion of the intertidal zone (increase in tidal prism) of the upper harbour and/or sedimentation in the entrance.

CHAPTER THREE : LUCAS CREEK SEDIMENTOLOGY

3.1 PHYSIOGRAPHY

Lucas Creek is a funnel shaped estuary that extends 6.5 km from the mouth near Salthouses Jetty to the township of Albany (Plate 3.1, Fig. 3.1). At low tide a considerable proportion of the estuary is exposed as low gradient intertidal flats with extensive mangrove vegetation (Table 3.1).

Sedimentary Environment	Surface Area at Spring Low Tide (ha)	% of Total Area
Low tide channel	39.6	26
Intertidal flats	68.3	45
Mangroves	43.2	29

Table 3.1 : Major sedimentary environments in Lucas Creek (Figs. 2.4 and 3.1)

The bed of the main channel falls 3.4 metres (+ 1.3 m CD to - 2.1 m CD) from L1 to L18, an average slope of 1:18000 (Fig. 2.7). In the upper reaches the tidal channel is very narrow, recent muddy sediments are thin (Fig. 2.7) and low tide exposes bed rock and rubble bars which impede ebb tide drainage (Plate 3.2). Between L5 and L11 the estuary widens locally but low tide waters are confined to a narrow central channel (Fig. 3.1). Between L12 and L15 the estuary widens to 1.2 km where the Te Wharau Creek inlet joins the main tidal waterway (Plate 3.3). Here the wide intertidal mudbanks are up to 4 metres thick (Fig. 2.6), and support extensive mangrove communities in the Te Wharau arm of the estuary (Fig. 3.1). In the entrance reach (L15-L18) the estuary narrows to 200 m and deepens towards the mouth. The bulk of recent marine sediments are situated in the entrance area where they are up to 10 metres thick (Fig. 2.7). The mouth of the estuary terminates in a 7 metre submarine cliff.

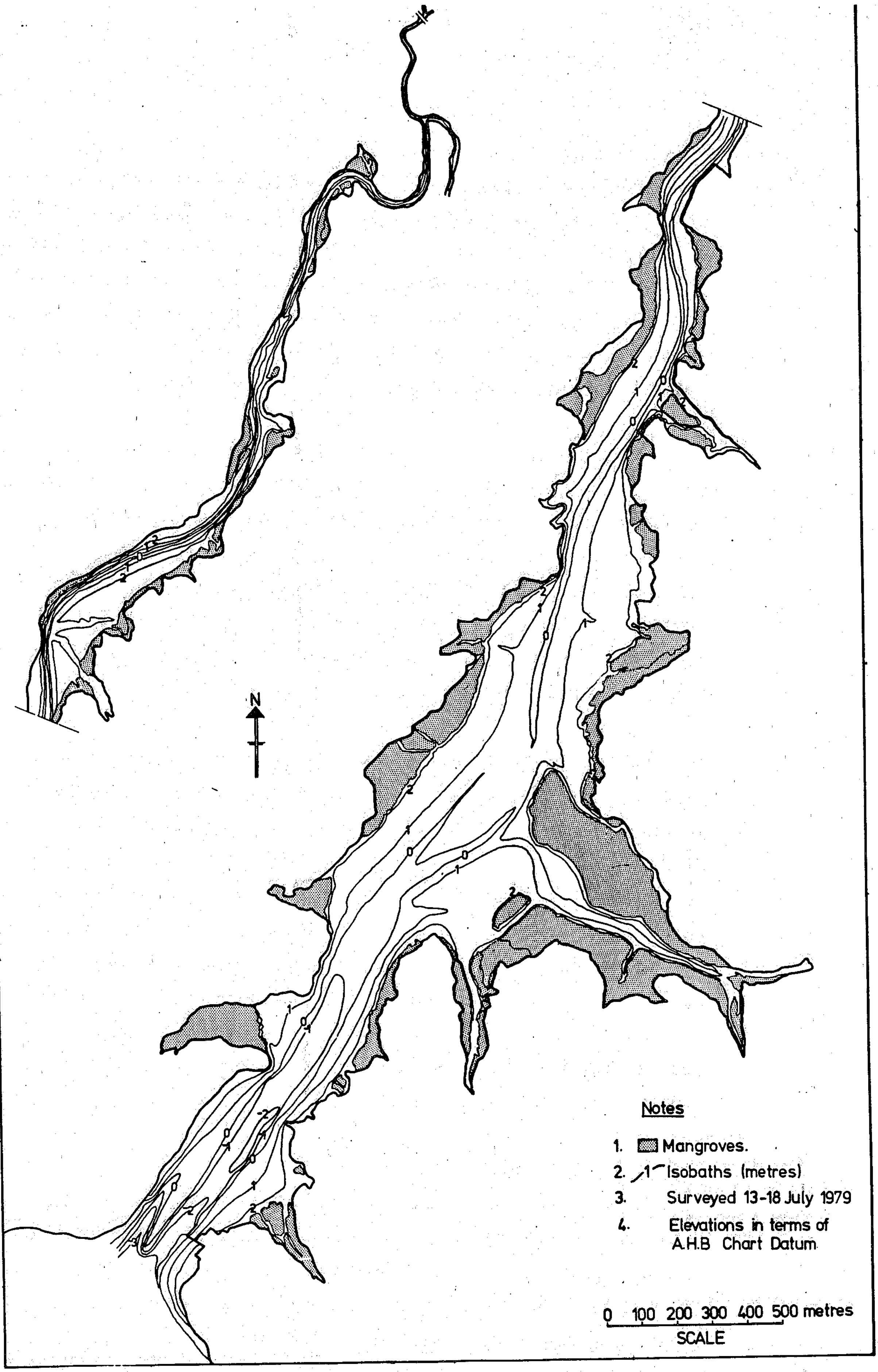

Figure 3.1 : Bathymetry of Lucas Creek. Note bifurcations in the main channel near the entrance and in the vicinity of the Te Wharau delta. Mangrove stands normally grow above 2.3 m CD.

3.2 SEDIMENT SOURCES

The geological, pedological and morphological characteristics of the catchment show that dominantly mud and very fine sand size material is available for erosion by overland flow (Jessen 1983). Field examination of stream bank erosion debris, stream channel deposits (including weir pond debris) and flood debris confirms the majority of sediment transported by the streams is mud and very fine sand (i.e. material transported largely as suspended load).

Suspended solids comprised largely of mineral material, originates from the Lucas and Oteha catchments that discharge into the headwaters of Lucas Creek, with a lesser contribution from the Te Wharau Stream (van Roon 1983, and Fig. 3.2). Suspended solids input to Lucas Creek for 1980 and 1981 were calculated from measurements at the Lucas and Oteha stream water level recorder stations (Table 3.2). The techniques, and assumptions made in the calculations are detailed in van Roon (1983). No bed load data are available.

The Oteha data show that the annual mass transport can vary markedly depending on the size and frequency of storm events. For instance 72% of the 1980 sediment load resulted from one days discharge (15 March 1980) associated with cyclone Sina. The next largest storm produced 7% of the 1980 load on 20 July 1980. 86% of the 1980 sediment yield was contributed in 7 flow days (2% of the annual flow duration time). The total sediment yield for 1980 was nearly 5 times that for 1981 primarily due to the cyclone Sina storm. This storm alone produced 3.5 times the 1981 total sediment yield. The shorter Lucas stream record shows similar features. It is clear that floods have a major influence on sediment yield.

3.3 SURFICIAL SEDIMENTS

Surficial sediments were sampled by box dredge sampler. Textural analyses were carried out by pipette analysis (mud fraction) and dry sieving (sand and gravel fraction), and nutrients were determined by chemical methods detailed in Fry and Hume (1983). Comparisons are drawn between Lucas and the adjacent Hellyers Creek sediments to demonstrate that the trends observed are not unique to Lucas Creek and

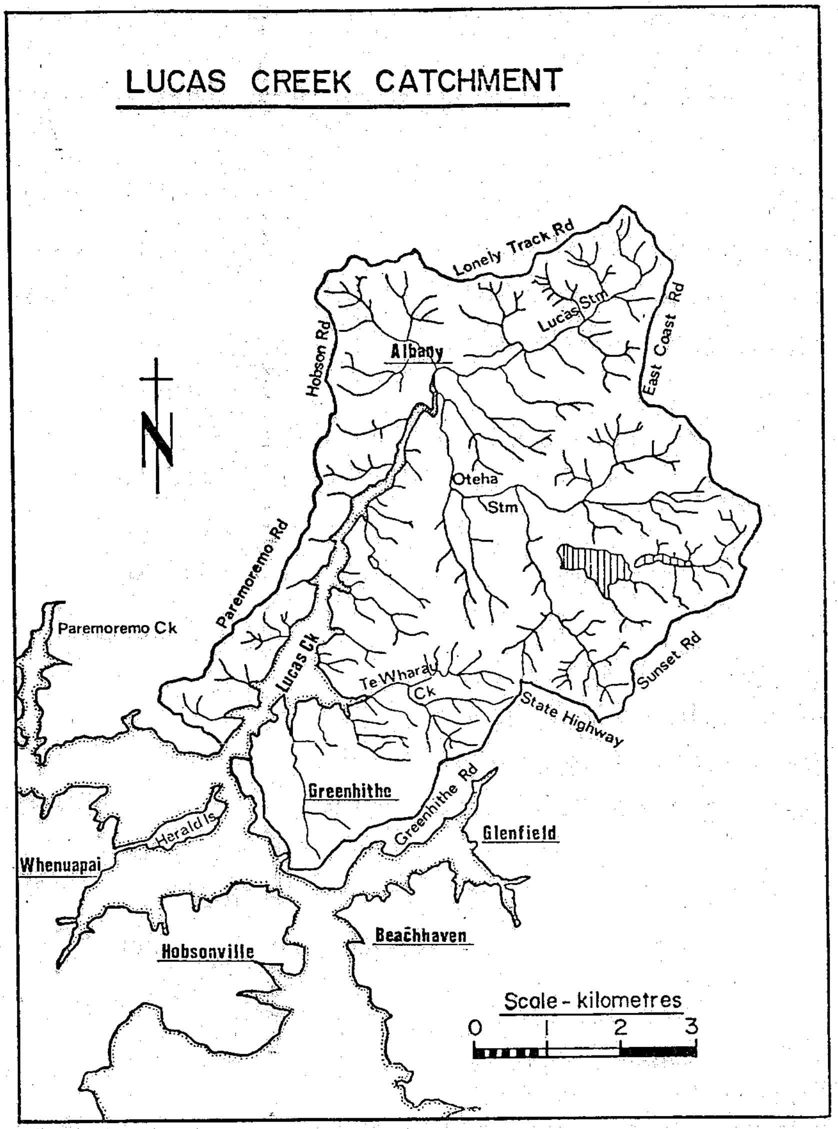

Figure 3.2 : Lucas Creek catchment. Most of the catchment is drained by the Lucas (6.26 km^2) and Oteha (12.13 km^2) streams.

are perhaps of much wider significance.

Surficial sediments are generally fine-grained and are classified as muds and sandy muds (Fig. 3.3) There is considerable variation in sediment texture from the estuary channels to the mangrove areas (Fig. 3.4). Channel sediments are relatively high in sand and low in silt and clay. In places in the upper estuary reaches the channel floor is

	OTEHA	LUCAS
<u>1980</u>		
Mean yield (tonnes/day)	5	No data for first half of year
Total yield (tonnes/yr)	1947	
Specific yield (tonnes/ha)	2	
	72% 1980 load on 15.3.80	
	7% 1980 load on 20.7.80	
	86% 1980 load in 7 flow days	
<u>July to December 1980</u>		
Mean yield (tonnes/day)	2	3
Total yield (tonnes/yr)	447	539
Specific yield (tonnes/ha)	0.4	0.8
	29% 0.5 yrs load on 20.7.80	45% 0.5 yrs load on 20.7.80
	65% 0.5 yrs load in 7 flow day	79% 0.5 yrs load in 7 flow days
<u>1981</u>		
Mean yield (tonnes/day)	1	1
Total yield (tonnes/yr)	402	392
Specific yield (tonnes/ha)	0.3	0.6
	9% 1981 load on 16.6.81	12% 1981 load on 24.8.81
	33% 1981 load in 7 flow days	42% 1981 load in 7 flow days

Table 3.2 : Mass transport of suspended solids (non-filterable residue) as measured for catchments Oteha Stream at Days Bridge (12.13 km^2) and Lucas Stream at Gills Rd (6.26 km^2). Data from van Roon 1983.

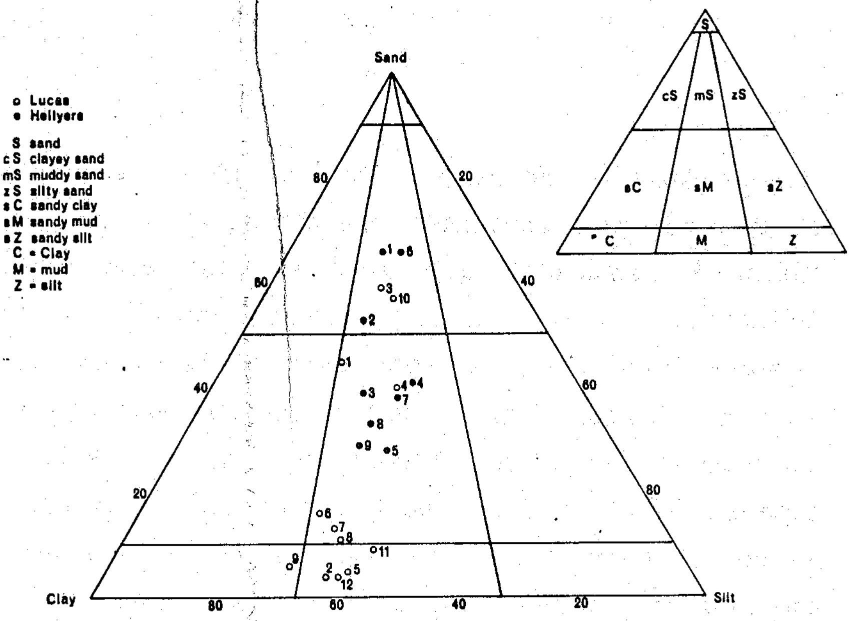

Figure 3.3 : Ternary diagram for Lucas and Hellyers Creek surficial sediments. Textural size classes are defined in Appendix I.

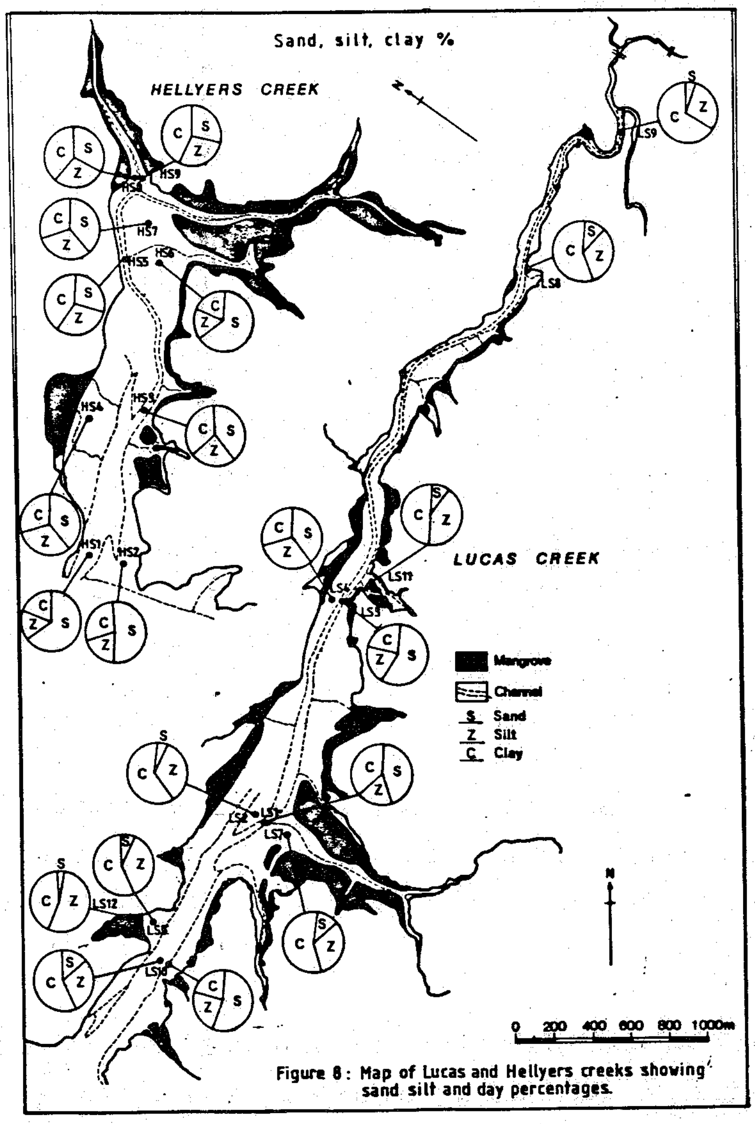

Figure 8 : Map of Lucas and Hellyers creeks showing sand silt and day percentages.

Figure 3.4 : Sand, silt and clay present in Lucas (23.4.80) and Hellyers (17.6.80) Creek surficial sediments.

swept clean of sediment. In the lower reaches soft muddy channel floor sediments sometimes are armoured by shell lag deposits. The mudbank sediments are high in silt and clay and low in sand. Sediments of the shoreline embayments have little sand and are dominated by muds. In contrast to the across channel differences in sediment texture, the longitudinal changes in particle size commonly associated with tidal inlets, are not evident. Surficial sediments sampled at 3 sites in both Lucas and Hellyers creeks show "quasi-seasonal" fluctuations in texture being coarsed textured in winter compared to summer (Fig. 3.5; Fry and Hume 1983).

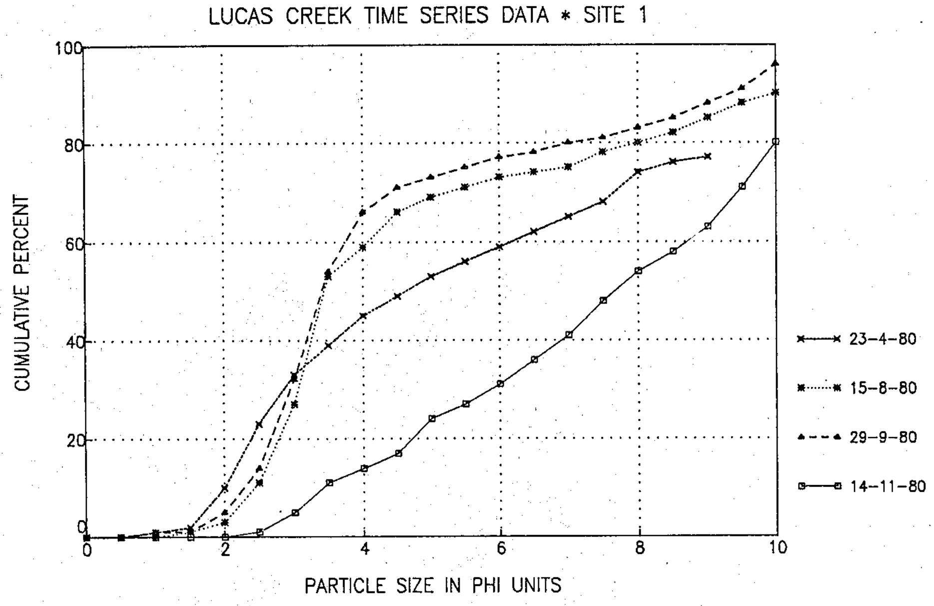

Figure 3.5 : Textural variations in surficial sediments sampled on four separate occasions at site LS1 (Fig. 3.4). The sediments are coarser in the winter and finer in the summer.

Overall, dead and living animals and plants are not a significant component of Lucas Creek sediments. Both $CaCO_3$ and organic carbon are generally less than 4% dry weight (Bioresearches 1981, Fry and Hume 1983).

Clay mineral distributions in the <2 μm size fraction of Lucas Creek sediments (Fig. 3.6) determined by XRD analysis show that the average

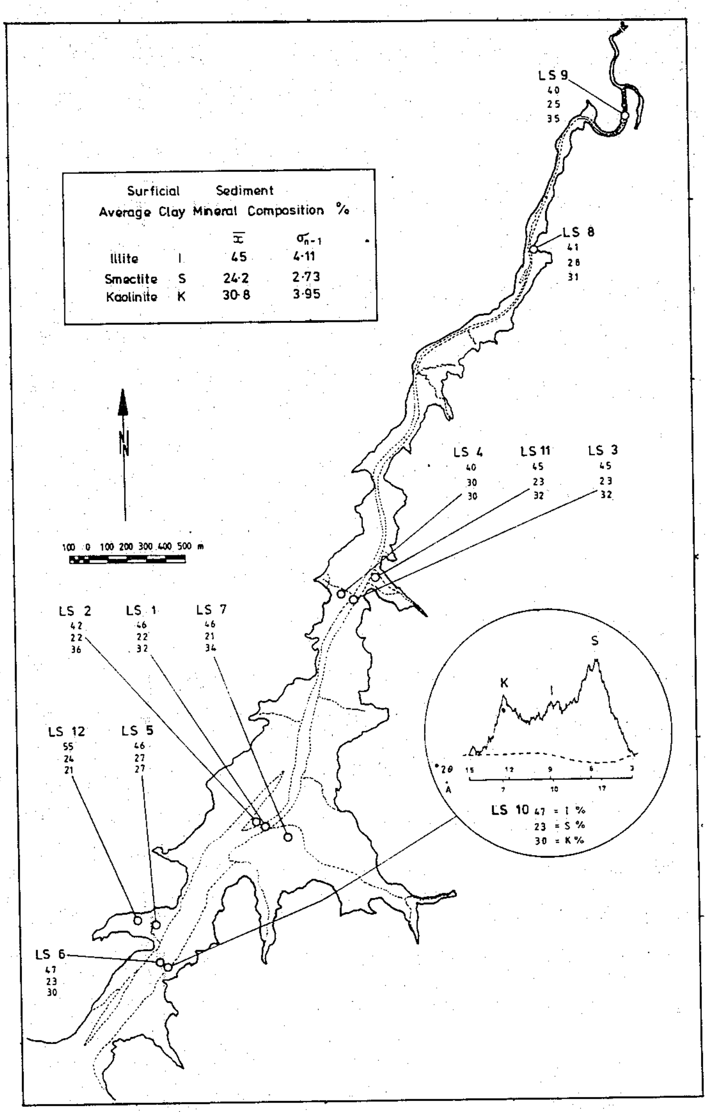

Figure 3.6 : Clay mineral abundance in Lucas Creek sediments. The diffractogram shown for LS10 is typical of the poorly crystalline clay mineral suites.

clay mineral composition to be illite 45%, kaolinite 31% and smectite 24%. The clay mineral distributions show no discernable trends either from the headwaters toward the mouth or between channel bed and tidal flat samples. Hellyers Creek samples show a similar distribution (Fry and Hume 1983).

3.4 SEDIMENT PROCESSES

Tides

Because the tidal range is a significant proportion of the water depth at many points in the estuary, the cyclic back-and-forth flushing of tidal currents is the principle mechanism for transporting and reworking estuarine sediments.

Sedimentation processes at L5, Wharf Rd, (Figs. 2.4 and 3.7 and Plate 3.2) are considered representative of the upper estuarine reaches of Lucas Creek. The tidal flow at this point varies markedly across the section and throughout the tidal cycle, because of the variable channel morphology and the 2 to 3 metre tide range.

On the tidal flats (V1 and V4; Fig. 3.8) conditions are favourable for deposition for 3-4 hours either side of high tide when flood and ebb spring tide velocities do not exceed 0.2 m/s. Sedimentation of mud from suspension is only appreciable if current speeds drop below 0.2 m/s (Fig. 1.3 and Einstein and Krone 1962). Peak velocities on the tidal flats (less than 0.2 m/s) are far below that necessary to rework the muddy tidal flats (c.f. Fig. 1.3) resulting in net deposition of sediment over the tidal cycle. However, complete settling of suspended material is prevented by its small fall velocity. During the 3-4 hours either side of low water the tidal flats are dry and subaerial exposure can greatly aid consolidation (e.g. Terwindt and Breusers 1972). Sandy muds up to 1.5 metres thick have accumulated on the channel flanks (Fig. 2.6 and Plate 3.2).

In the central low water channel area (V_3) conditions are favourable for suspended sediment deposition (i.e. $V < 0.2$ m/s) for approximately 3 hours about high water and low water (Fig. 3.8). Despite this the channel bed is barren of sediment in places, perhaps due to erosion by turbulent freshwater and ebb tide drainage generated by a rock bar immediately upstream of the site (Plate 3.2). Upstream of L5 ebb tide drainage is impeded at lower stages of the tide by rock bars, and the ponded areas upstream of the bars form natural sediment traps.

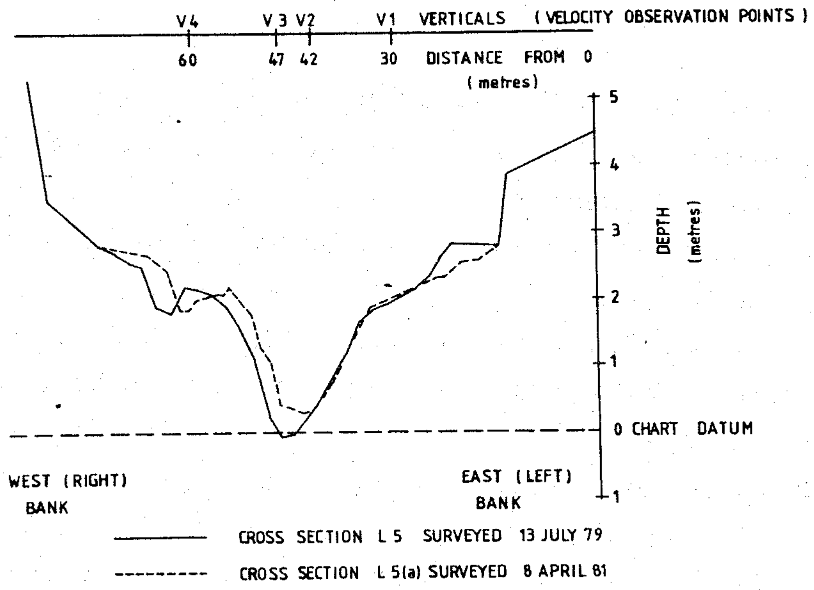

Figure 3.7 : Channel cross section profile at L5.

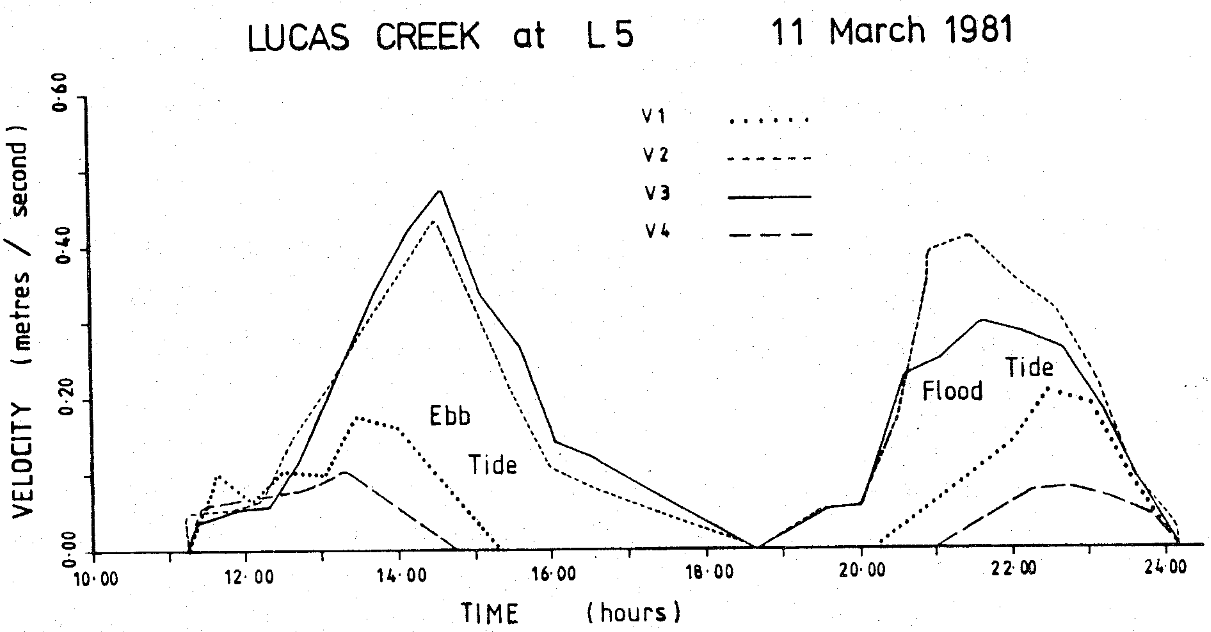

Figure 3.8 : Spring tide velocity-time profiles (mean in vertical) for verticals V1-V4 (Fig. 3.7) for Lucas Creek at L5. Measurements made on 11 March 1981 (McLachlan and Hume 1981).

Downstream of L5 where the estuary widens, current velocities decrease, resulting in a reduction in the sediment transport capacity, and sedimentation occurs. At L7 (Fig. 2.4), for instance, a wedge of unconsolidated sediment that thickens to nearly 4 metres has built-up on the channel bend (Fig. 2.6). In the lower channel reach between L11 and L15 (Fig. 2.4) a complex array of intertidal bars, deltas and channels has formed in a major area of sediment deposition (Fig. 2.6). From the Te Wharau subestuary an intertidal delta stabilised by mangrove bush builds out into the main channel (Fig. 3.1 and Plate 3.3). Its distal end is truncated by ebb tide flows in the main channel which are strong enough to rework fine sediment and concentrate lag shell deposits on the channel flank (Plate 3.4). In the centre of the main channel an intertidal bar (Fig. 3.1) separates flood tide flows concentrated in the western blind channel from ebb tide flows in the eastern main channel. In the entrance reach a thick sequence of unconsolidated sediment has built-up attaining maximum thickness at L16/17 (Fig. 2.6).

Sedimentation processes at L17 are considered typical of those in the entrance reach. Here the channel cross section is slightly asymmetrical being deepest on the western flank (Figs. 2.4, 3.9 and Plate 3.3).

At tidal flat site (V_1) weak spring tidal currents (Fig. 3.10) are favourable for sediment deposition for the 3.5 hours either side of high tide when water covers the site and when the tide recedes the deposited sediment can consolidate subaerially.

In comparison the deep western channel flank (V_8) is explained by the strong flood dominated flows (up to 0.5 m/s) constricted against a headland. This is undoubtedly related to the flows at the mouth of the creek where the bathymetry indicates a subtidal bar separates flood (western) and ebb (eastern) flows (Fig. 3.1 and Plate 3.3).

Small tidal velocities make conditions favourable for sediment deposition throughout most of the ebb tide phase. Extremely fine grained mud-rich sediments on the western flank of the inlet at L16/17

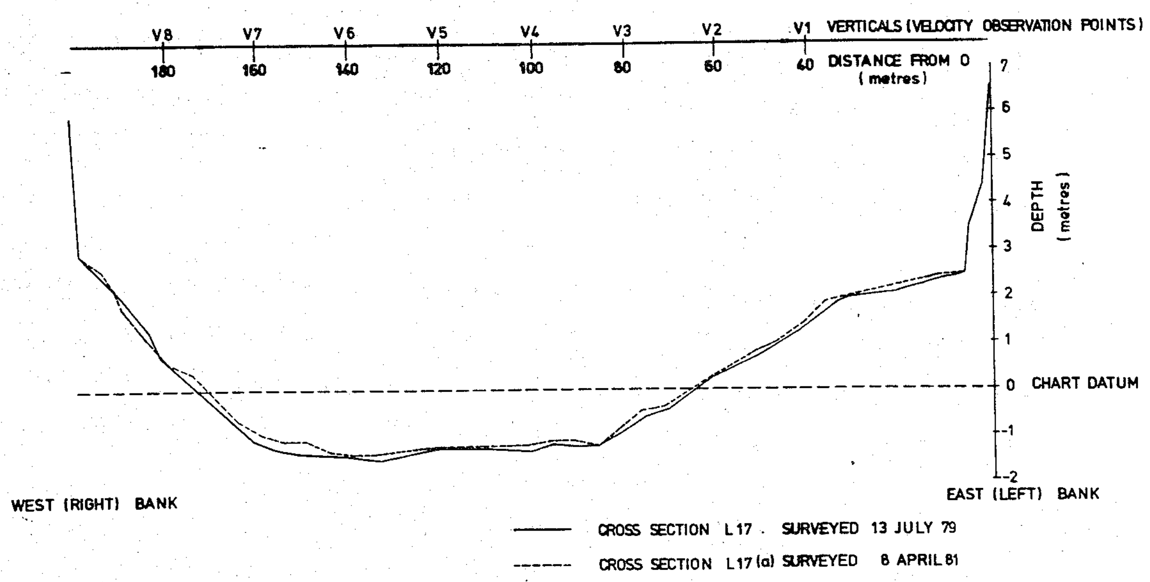

Figure 3.9 : Channel profile at L17. Note the difference in scale compared to Fig. 3.7.

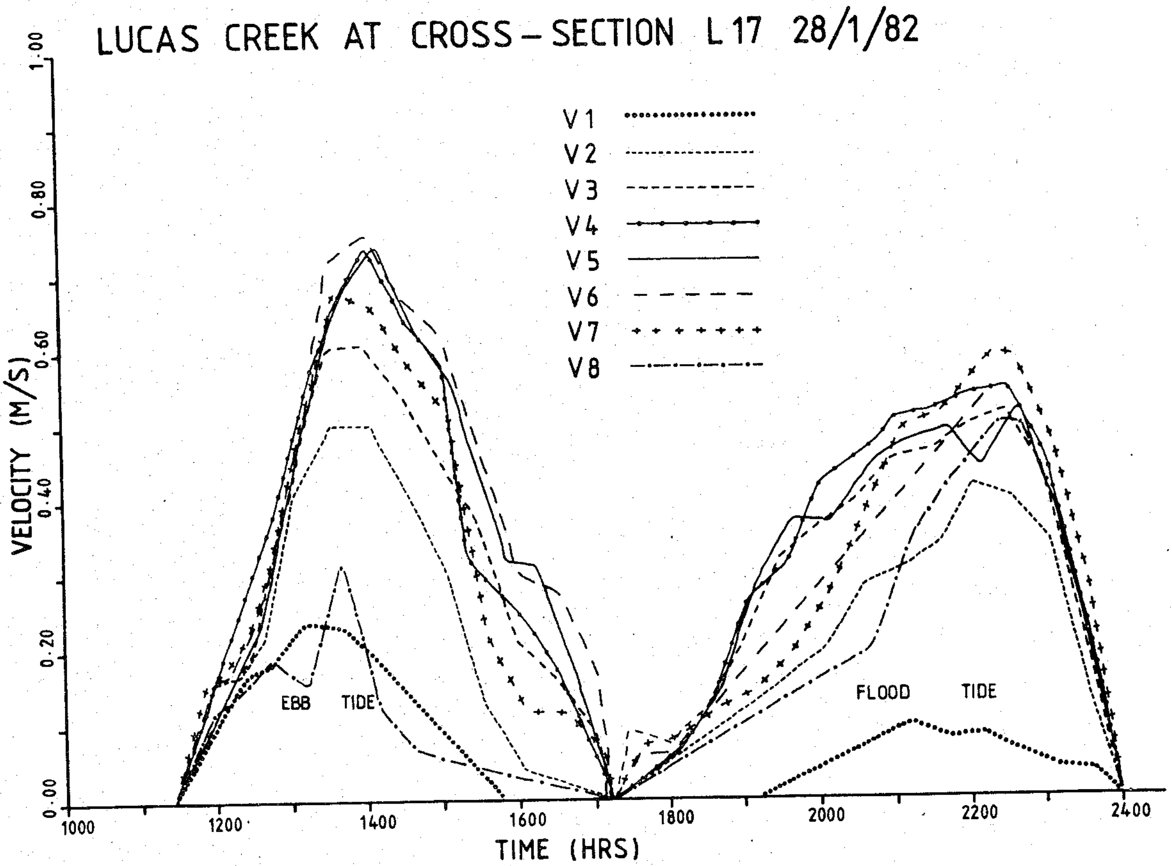

Figure 3.10 : Spring tide velocity-time profiles (mean in vertical for verticals V1-V8 at L17. Measurements made on 11 March 1981 (McLachlan and Hume 1981).

(Fig. 2.4) may represent flood tide deposits and perhaps suspension load material from outer estuary sources. Here, peak spring tide velocities are only 0.13 m/s and deposition will occur for much of the time that water is present at the site.

In the central channel at L17 (V4-V5) ebb velocities dominate over flood suggesting that more erosion and resuspension is likely to occur on the ebb tide (Fig. 3.10). The most favourable conditions for sedimentation occur for the short periods when velocities drop off toward slack water low and high tide.

Nearer the entrance of Lucas Creek strong ebb tide flows maintain a deeper channel on the eastern side of the estuary (Fig. 3.1 and 2.6). In the entrance, complex flows are sufficient to concentrate muddy-sandy shell gravels on the eastern channel flank (Bioresearches 1981). Quieter flows on the west of the entrance are reflected in finer sandy sediments.

Compared to the channels, the tidal flats are the most favourable sites for deposition as tidal currents are weaker for longer periods and, when the tide recedes, the freshly deposited sediment dewaters and consolidates subaerially. Sediment deposited in the channels at high and low slack tide does not have the same chance to consolidate, is situated in areas of relatively high current flow (the channels) and is more likely to be reworked.

The substantial difference in neap and spring tidal prism for Lucas Creek (1.6 x 10^6 m^3 and 2.3 x 10^6 m^3 respectively) has a pronounced effect on the magnitude of velocities and discharges, tidal excursion and flushing and thus on the sediment transporting capacity of neap and spring tides.

Neap tide velocities are about 70% those of spring tides (Figs. 3.8 and 3.10). For this reason sedimentation is likely to be favoured on neap tides when velocities are too low to rework sediment for most of the tidal cycle (cf. Fig. 1.3). Furthermore, increasing current velocity - time asymmetry, brought about by decreasing tidal range, and corresponding longer flood slacks, will argument the sedimentation potential during neap tides. A cycle of net erosion and sedimentation corresponding to neap and spring tides, with respect to the suspended sediments, reported in other estuaries (e.g. Wright *et al* 1975, Allen *et al* 1976) may well exist in Lucas Creek.

Stream flows

Flood events can significantly alter tidal forces, and associated sedimentation patterns in estuaries because floods carry the bulk of sediments to the estuary, they may generate currents that rework surficial sediments, and result in a net export of water, and therefore suspended solids.

Field observations confirm floods influence sedimentation patters in the headwaters of Lucas Creek. After the 15 April 1978 storm, debris lines in the trees indicated that the water level at L1 (Fig. 2.4) rose to 2.4 m above spring tide level. Downstream of L2 silty unconsolidated sediment up to 10 cm thick was deposited on the grassed berms bordering the tidal flats. The (Telethon) 30 June 1979 storm caused sediment stripping of tidal flat sediments to a depth of 30 cm about the base of mangrove shrubs on the eastern flats immediately upstream of L5, and bank collapse downstream along the main channel flanks and in tidal flat drainage channels. Velocities at L5 (Wharf Rd) were sufficient to move concrete blocks along the tidal flats. Interestingly flood debris (presumably trees) acted as sediment stripping tools in the upper reaches of Lucas Creek producing deep grooves along the tidal flats parallel to the channel axis (Plate 3.5).

Observations from Salthouses boatyard (L18) near the entrance of Lucas Creek suggest that during times of larger river inputs the ebb tide phase is increased to well beyond the normal 6.5 hours. On some occasions the movement of keel boats on swing moorings in the area suggests the tide does not flood at all. It is probable that in big flood events surface water outflow is probably maintained for a long time, but that flood tide waters intrude along the bottom of the estuary.

Unfortunately, there is no flow data available for flood assisted flows in the estuary. However, calculations of a range of stream characteristics for the headwaters (catchment above L5), and the entrance (catchment above L17), can be compared with tidal data (Table 3.3 and Figs. 3.11 and 3.12) which allows an assessment of the role of stream flows in controlling sedimentation patterns.

The stream data (Table 3.3) show mean annual discharges are 10 to 20x summer low flows. Flood events significantly increase stream flow. For instance, a relatively small 1 in 2 yr flood event will produce a peak discharge 26x mean annual discharge.

<u>At L5 (Wharf Road)</u> summer low flows and mean annual discharges and flow volumes over the tidal cycle are insignificant compared to tidal flows and volumes (Fig. 3.11) and will not influence tidal sediment transport. Peak discharges and flow volumes per tidal cycle due to a 1 in 2 yr flood are more comparable to tidal water statistics while the 1 in 5 yr freshwater input is clearly larger than spring tide flows and volumes. Extreme events such as the 1 in 50 yr flood are orders of magnitude larger than tidal events.

The data suggest that large storm events will push the limit of freshwater excursion (with its sediment load) downstream of L5, toward the estuary mouth. At some point interaction of opposing tidal and stream flows will result in velocity drop-off and sedimentation. Obviously the effects will be complex and depend on whether the stream flood event coincides with a flood or ebb tide, the tidal range at the time and the coincidence of the flood and tidal peaks. High suspended solids concentrations will not result in sediment build-up if flow velocities are too high to allow deposition (e.g. de Mowbray 1983).

Velocities generated by peak flood water flows through the estuarine headwaters are large and, particularly if they coincide with the ebb tide, will be adequate to scour surficial sediments in the low tide to middle tidal flat areas (cf. Table 3.3 and Fig. 1.3). Bed scour may be accelerated by a drop in salinity and water temperature, and an

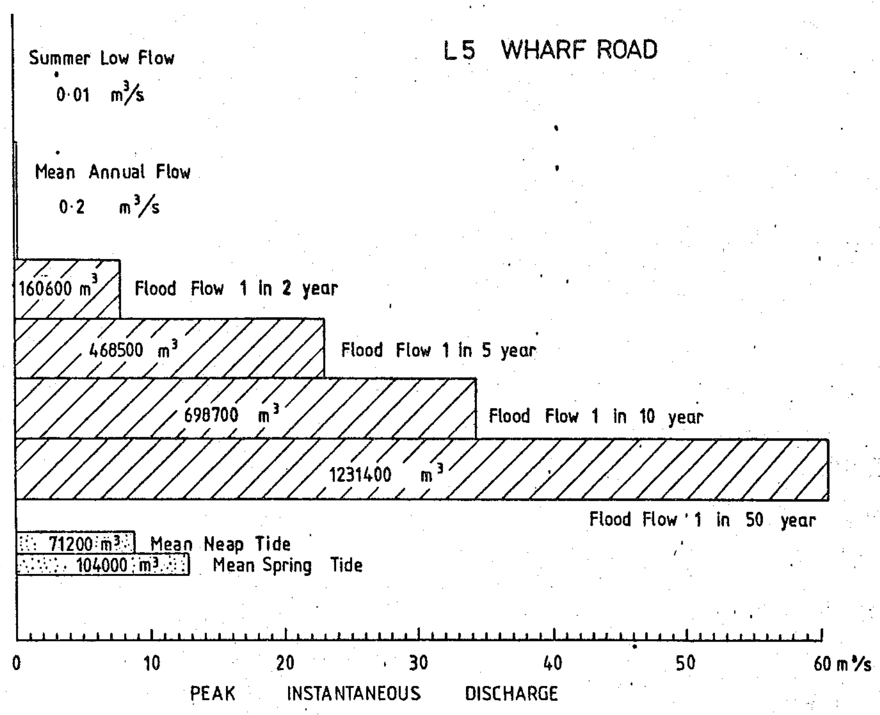

Figure 3.11 : Comparison of stream inflows and tidal flow at L5 in Lucas Creek (Fig. 2.4). The distance along the x-axis shows peak instantaneous discharge and the area of the histogram bars the volume per tidal cycle.

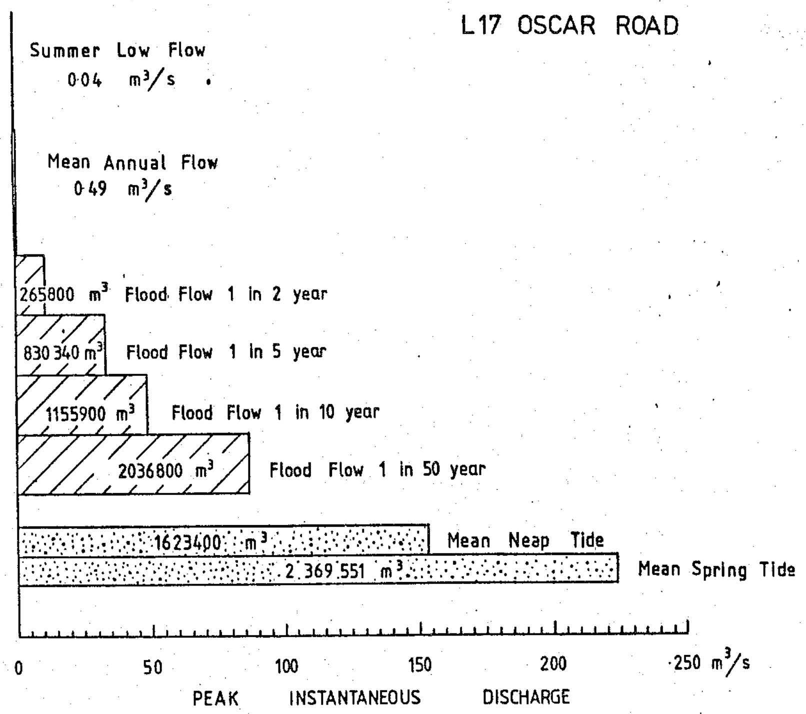

Figure 3.12 : Comparison of stream inflows and tidal flow at L17 in Lucas Creek (Fig. 2.4). The distance along the x-axis shows peak instantaneous discharge and the area of the histogram bars the volume per tidal cycle. (Note the difference in scale cf. Fig. 3.11).

	HEADWATERS L5			ENTRANCE L17		
	Volume (m^3)	Discharge (m^3/s)	Velocity (m/s)	Volume (m^3)	Discharge (m^3/s)	Velocity (m/s)
FRESHWATER						
Summer Low Flow	606	0.01	-	1966	0.04	-
Mean Annual Flow	10700	0.24	-	22095	0.49	-
Flood Events						
1 in 2 yr	160600	7.9	1.0/0.1	265800	11.4	<0.1/<0.1
1 in 5 yr	468500	23.0	2.9/0.4	775000	33.1	0.2/<0.1
1 in 10 yr	698700	34.3	4.3/0.5	1155900	49.4	0.3/0.1
1 in 50 yr	1231400	60.4	7.6/0.9	2036800	87.0	0.5/0.2
TIDES						
Neap (mean)	71200	8.7	0.25	1623400	154	0.39
Spring (mean)	104000	12.7	0.36	2369600	224	0.56

Table 3.3 : Estimates of volume, discharge and velocity for a variety of stream inflows (calculated from Smith 1983) and tides (calculated from McLachlan and Hume 1981) at L5 and L17 in Lucas Creek. The summer and mean annual streamflow data record total input volumes, and steady flow discharge to the estuary per tidal cycle (about 12.4 hr). Flood event data records total input volume, and peak discharge for the flood event. For the headwaters (L5) the flood duration time is about 13 hours i.e. similar to a tidal cycle. The flood (mean in section) velocities (e.g. 1.0/0.1) are those generated by peak freshwater flows through the estuary sections, at L5 and L17, at low/high tide respectively. Tidal volumes (tidal prism), peak discharge and mean in section velocity are calculated from tidal gauging data.

increase in suspended solids accompanying floods (McDowell and O'Connor 1977). The role of sediment stripping by flood waters in preventing a build-up of sediment in the upper reaches of Lucas Creek, is indirectly supported by the absence of sediment from the floor of the channel at L2 and L5, and by the low net sedimentation rate, evidenced by the veneer of tidal flat sediment 1 to 1.5 metres thick (Fig. 2.6) that equals the sum total of sediment deposition since sea level attained at its present level some 6000 years ago.

Nearer the entrance at L17 only the larger flood events have discharges and volumes that approach those of the tides, and the influence of floods on sedimentation patterns will be far less pronounced. Floods are unlikely to generate velocities large enough to strip sediments (cf. Table 3.3 and Fig. 1.3). If strongly stratified flows developed, the exit of sediment laden freshwater over the top of less turbid incoming tidal waters, would provide an important mechanism for expelling flood input suspended sediment from the estuary.

<u>Waves</u>

Sediment reworking by wind wave action can be an important process in sorting and redistributing estuarine surficial sediments. High orbital velocities produced by waves entrain fine sediment that can be transported by much weaker tidal currents (Fig. 1.3). In Lucas Creek suspended solid plumes generated in intertidal areas, by waves at the tidal front indicate this process is operating.

Wind waves in the entrance reach and Te Wharau area are generally less than 30 cm high and of about 1-2 second period. In 1 metre water depth these waves generate mean velocities of 0.7 to 0.3 m/sec (Coastal Engineering Research Centre 1977) which will resuspend fine sands and coarse silts, but not the cohesive fine silts and clays (Fig. 1.3). Conditions most favourable for sediment reworking by wave action are restricted to periods of mid to high tide when tidal flats are covered by water, and to times when winds blow northeast or southwest along the axis of the estuary.

It was initially thought that the "quasi-seasonal" changes in surficial sediment texture were evidence of the importance of sediment reworking by wave action. However, comparison of the 1980 wind records from Whenuapai with 1980 textural variations (Fig. 3.5) showed that mean monthly wind speed (based on hourly values) were constant in mid to late autumn and winter (6-7 m/s) but increased in spring and summer (8-12 m/s), whereas sediments coarsened in winter and fined in summer i.e. coarsening sediments do not coincide with higher wind speeds. Furthermore, those winds with the longest fetch blow from the northeast or southwest and occur largely in spring and summer. Therefore, it appears that wind generated wave activity is not an important factor contributing to "quasi-seasonal" coarsening and fining of sediment.

During the winter period the estuary is subject to more frequent and larger freshwater inflow events that result in larger amounts and coarser grained material being delivered to the system. In the upper reaches of Lucas Creek current velocities generated by these events strip and rework unconsolidated fines deposited in quieter periods. It appears that variations in fluvial sediment texture accompanying predominantly winter flood events is a more likely cause of "quasi-seasonal" changes in estuarine sediment texture than wave action.

Net Deposition

A crude estimate of the maximum average annual sedimentation rates in Lucas Creek estuary can be made from the sediment input data (Table 3.2). The total mass transport to the estuary from the Lucas and Oteha Streams was approximately 794 tonnes in 1981 and about 5 times this in 1980 (about 3971 tonnes). Assuming half this amount (2383 tonnes) to be a "typical annual sediment load", and that if all of this was transported to the estuary and deposited, it would have a volume of:

$$\frac{2383 \text{ tonnes} \times 1000 \text{ kg}}{1100 \text{ kg/m}^3} = 2166 \text{ m}^3$$

(where 1100 kg/m^3 is the density of surficial sediments, Section 1.4). If spread as an even thickness layer over the bed of the estuary (excluding the low water channel area where substantial sediment accretion is unlikely because of relatively high environmental energy) it would form a layer:

$$\frac{2166\ m^3}{112 \times 10^4\ m^2} = 0.002 \text{ metres thick}$$

The 2 mm per annum maximum sedimentation rate would increase slightly if bed load were included. A single storm the size of cyclone Sina would deposit a similar amount of sediment, whereas the 1981 total sediment load would form a layer only 0.6 mm thick. In actual fact the sediment would not be spread as an even thickness layer but would distribute itself according to environmental energy within the system. These rates are slightly less than the 3 mm/annum calculated from the pollen data (Fig. 2.10).

Field observations suggest much of the sediment is flushed from the estuary before it can be deposited, so that net deposition would be less than that calculated above. After storms, sediment plumes from the Waitemata Harbour extend far out into the Hauraki Gulf. Some idea of the capacity of Lucas Creek to expel input suspended sediment can be gained from estimates of flushing time. The flushing time or residence time is the average time a <u>solute</u> particle remains in the system. For Lucas Creek best estimates of flushing time are 7 and 11 tidal cycles for spring tides and neap respectively (Williams and Rutherford 1983). These values describe the minimum time it takes for suspended sediment to be flushed from the system since suspended material will settle out only if the velocity falls below a critical transport value (Fig. 1.3). At many points of the estuary flood and ebb velocities are maintained at a high enough level to keep material in suspension throughout much of the tidal cycle and, given the short flushing time, much of the suspended load can be flushed out the entrance. Estimates of entrance water exchange suggest that once out of the entrance, less than 20-30% would be expected to return (Williams and Rutherford 1983).

3.5 SEDIMENT NUTRIENTS

Surficial sediments of Lucas Creek, sampled in April 1980, were analysed for their major nutrient components, namely total Kjeldahl nitrogen (TKN), total phosphate (TP), and readily oxidisable carbon

(ROC) (Fig. 3.13). The subtidal or channel samples averaged 1060

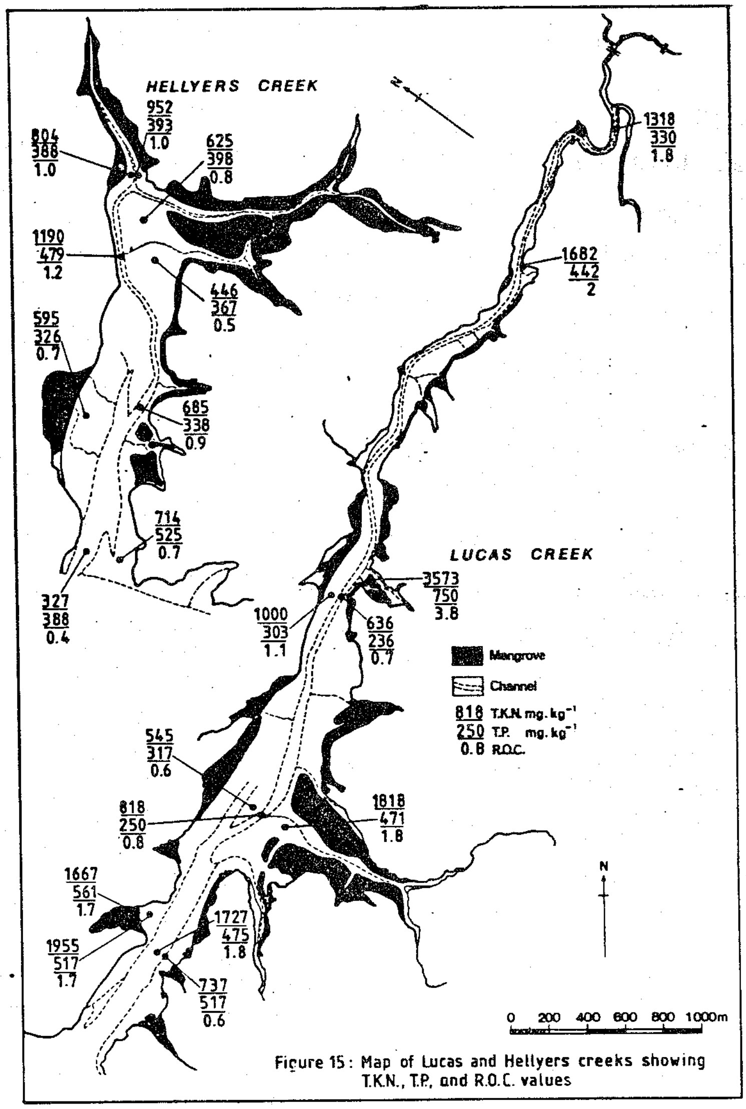

Figure 3.13 : Total kjeldahl nitrogen, total phosphorus and readily oxidisable carbon in Lucas (23.4.80) and Hellyers (17.6.80) Creek sediments.

mg.kg^{-1} TKN, 320 mg.kg^{-1} TP and 1.1% carbon. The mudbank or intertidal sediments contain about 50% more nutrients, averaging 1590 mg.kg^{-1} TKN, 467 mg.kg^{-1} TP and 1.68% carbon. The samples taken from the mangrove areas had the highest total nutrient content; 3573 mg.kg^{-1} TKN, 750 mg.kg^{-1} TP and 3.5% carbon.

There is a good correlation between increasing TKN and ROC and decreasing grain size in both Hellyers and Lucas Creek sediments (Fig. 3.14). For instance a clay size sample from a mudbank might be expected to have 4 times as much TKN and ROC as a coarse silt sample from an adjacent channel area. TP shows no simple relation to grain size. Furthermore, replicate sampling suggests that 20% of the variation in TKN, 15% in TP and 30% in ROC is due to errors inherent in the sampling technique (Fry and Hume 1983). The relationship between TKN and ROC (Fig. 3.14) has been observed elsewhere in terrestrial soils and estuarine sediments and suggests the nitrogen in the sediments is closely associated with the organic fraction (e.g. Smith and McColl 1979).

The coincidence of increasing TKN and ROC with decreasing grain size (Fig. 3.14) can be explained in part by the sediment rexture and composition. Fine grained sediments like those of the Upper Waitemata Harbour, have a large surface area to volume ratio and contain large volumes of interstitial water which provide ideal sorbtion conditions for nutrients. Upper Waitemata Harbour sediments contain clay minerals that have an exceptionally high surface area to volume ratio and high sorbtive capacity. The poorly crystalline and expandable illite and smectite clays, in particular, adsorb materials onto their surface and absorb them into their lattice framework. In comparison to TKN abd ROC there appears to be no selective sorption of TP onto finer grained compared to coarser grained sediments.

Repeated sampling at 3 sites in Lucas and Hellyers creeks throughout 1980 showed increases in sediment nutrient abundance in spring and summer suggesting a weak seasonal pattern. TKN and ROC, in particular, more than quadrupled and doubled respectively, in some Lucas Creek sediments (e.g. Table 3.4, Fry and Hume 1983).

Seasonal fluctuations of nutrients in estuarine waters and sediments have been well documented. Spring increases in nitrate and dissolved phosphate (Stevenson *et al* 1976), and the C/N ratio of the seston (Roman 1980) have been found. Smith and McColl (1979) reported generally higher levels of organic carbon and total nitrogen in spring and summer in Pauatahanui surficial sediments.

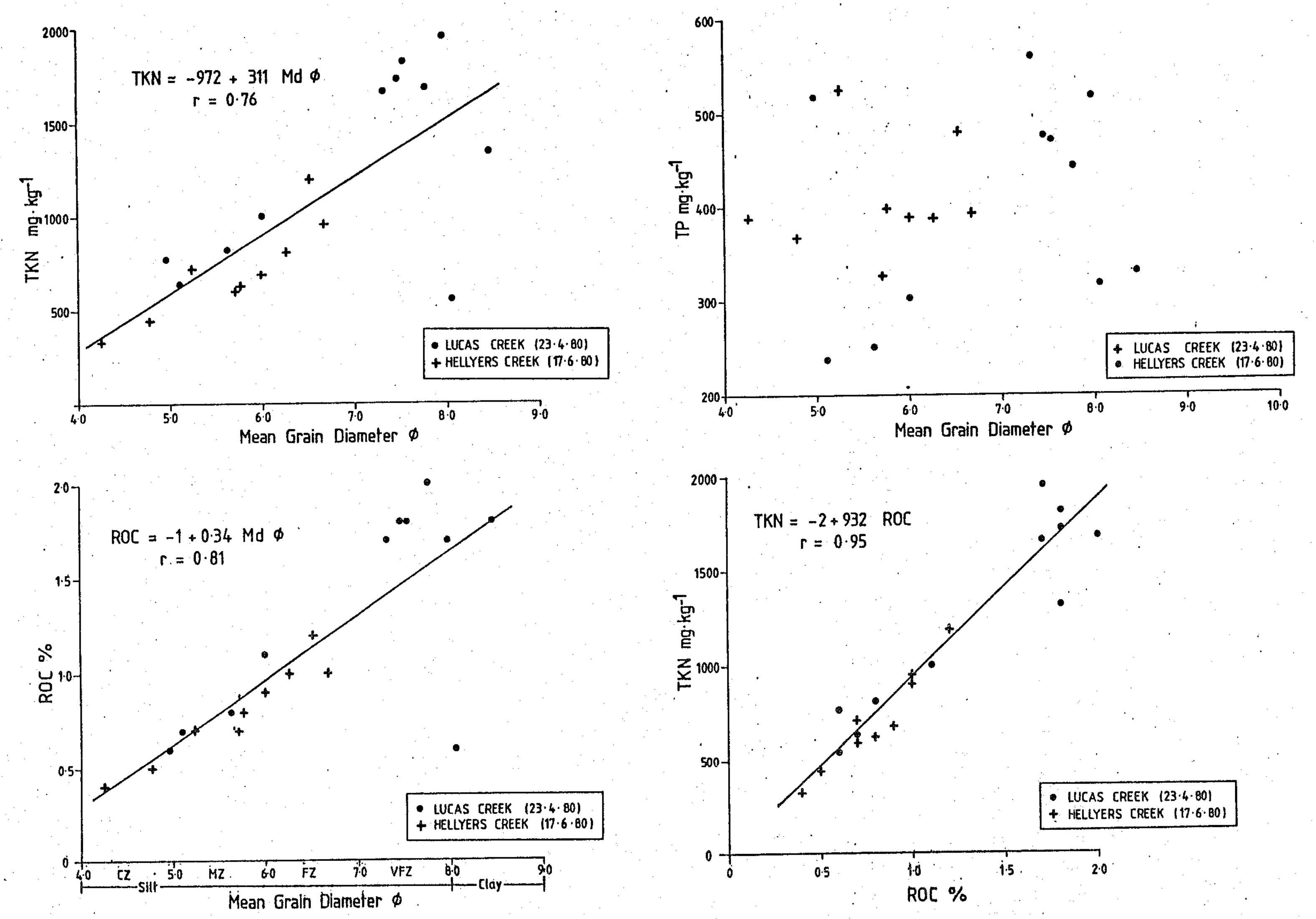

Figure 3.14 : Relationships between grain size, TKN, TP and ROC for Lucas (n = 11) and Hellyers (n = 9) creek surficial sediments (Fig. 3.13). The outlier (LS 2 at 8ϕ) reduces r values by about 14% for TKN and ROC vs mean grain diameter. The negative values for the y intercepts indicate the regression lines should not be extrapolated beyond the range of data points, and suggest for sediments of mean grain diameter larger than silt, the line becomes asymtopic to the x-axis.

Sample	Date	TKN $mg.kg^{-1}$	TP $mg.kg^{-1}$	ROC %	M_d ϕ
LS 1	23/27.4.80	818	250	0.8	5.63
LS 1	15.8.80	906	257	0.9	5.0
LS 1	29.9.80	1487	297	0.7	4.8
LS 1	14.11.80	3842	391	2.1	7.38

Table 3.4 : Variations in surficial sediment nutrients and texture at Site 1 in Lucas Creek (Fig. 3.6).

In Lucas and Hellyers creeks the spring and summer increases in nutrient levels, particularly those in TKN and ROC, coincide with a similar trend described for sediment texture (increasing sediment fineness) suggesting some common controlling factor. More detailed sampling and analysis is necessary to quantify any relationship.

3.6 GEOMETRIC STABILITY

The 'ideal' or 'equilibrium' estuary concept implies that a unique relationship exists between maximum tidal discharges and channel cross sectional area at mean tide level at all points up an estuary (Pillsbury 1956, McDowell and O'Connor 1977). A relationship of the

$$A = CP^n$$

type described in Section 2.6 has been shown to exist between the cross sectional and flow characteristics at various points along tidal rivers (e.g. Nelson 1977; van de Kreeke and Haring 1979).

To test if a similar relationship holds for the Lucas Creek tidal river, A and P values were plotted for measured cross sections L1 - L18 (Fig. 3.15). Mean spring tide conditions were selected for the plotting since one would expect peak flow to equate with maximum erosion and greatest influence on channel cross sectional area. In fact the fit for neap tides is only a little less than those for spring tides. Similarly, the best-fit line was attained using A

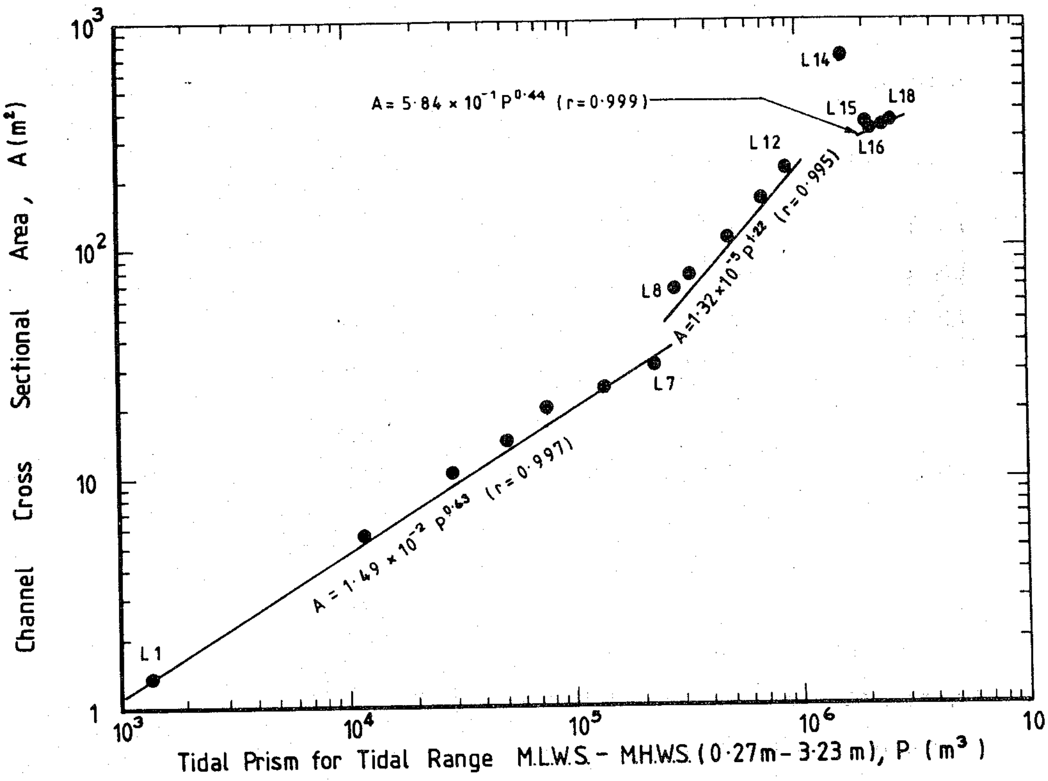

Figure 3.15 : Relationship between channel cross sectional area (below mean tide level) and spring tide prism upstream for L1 to L18 (Fig. 2.4).

measured below mean tide level (MTL) because peak flows are generated at about MTL and the channel cross section below this level would be most susceptible to scour. When the tide is above MTL, velocities become progressively weaker and deposition predominates over erosion. The plot of channel cross sectional area at MTL versus mean spring tide prism at the 18 cross section locations in Lucas Creek (Fig. 3.15) reveals that :

1 A simple

$$A = CP^n$$

relationship does not hold for the entire length of Lucas Creek and

2 Individual

$$A = CP^n$$

relationships appear to hold for three individual sections of the creek, namely L1 - L7, L8 - L12 and L16 - L18.

Locations not conforming to the relationships are L14 and L15. L14 lies in the Te Wharau delta confluence area and the line section runs up the Te Wharau Stream and one would not expect it to conform to the same simple relationship. L15 lies on the periphery of the delta area and as such may be influenced by processes unique to that area.

It is clear that there is no simple expression of geometric stability for Lucas Creek. It is hypothesised that: (1) the three sections of channel, L1 - L7, L8 - L12 and L16 - L18 are in a state of non-silting, non-scouring sedimentary equilibrium with spring tidal flows in the system, and that (2) the segmentation results from geomorphological or structural controls. L1 to L7 is the headwaters section above channel narrows (at L8 and L9) at which channel migration and bed erosion are restrained by bedrock outcrop (Fig. 3.1). L8 to L12 is the funnel-shaped reach extending south as far as the Te Wharau delta. At L12 there is a basement high that impedes drainage past this point. L16 to L18 is the entrance reach.

CHAPTER 4 : INFERRED IMPACTS OF CATCHMENT AND ESTUARY USE CHANGE

Anticipated changes in Upper Waitemata catchment and estuary use for the year 2000 are detailed in Moody (1983). It is possible to predict only in very general terms the nature, magnitude and location of the impact that these changes will have on estuarine sediments. This chapter identifies some of the effects of changing : (1) stream flow and sediment input to the estuary, in particular, that resulting from urbanisation of Lucas Creek catchment, (2) nutrient input to the estuary, and (3) commercial and recreational use of tidal waterways and associated reclamation, dredging and engineering works.

4.1 SEDIMENTATION

Upper Waitemata Harbour

Examination of historical sedimentation data suggests that it is likely that fine grained sediment will continue to accumulate in those areas where it does at present, that is, on the upper tidal flats, in the embayed areas of tidal creeks, and in the western harbour axis and the broad bays north and south of Herald Island where environmental energy is low, tidal flushing is poor and clay material flocculates on entering the marine environment (Fig. 2.11).

The sedimentation rate is most likely to show an increase where sediment input due to specific and localised land use changes, increases markedly over short periods of time and tidal currents are unable to transport the increased load. For instance, the Rangitopuni Creek is a potential problem area because it has the largest catchment to estuary area ratio, has extensive forestry development, and lies at the head of the harbour where flushing is poorest. A 20% increase in sediment input is expected by the year 2000 (Table 2.3). Provided forestry operations are carried out on small areas at a time the estuary will probably cope with the increased sediment load. Localised build-ups of sediment are likely to be flushed from the estuarine headwaters by flood events. Beyond the Rangitopuni estuary the effects of logging activities may increase water turbidity but sediment build-up will probably be undetectable.

In Brighams Creek where requirements for irrigation water for horticulture may be met by impounding flood waters, the sediment stripping capacity of floods in the estuary headwaters could be seriously reduced resulting in increasing deposition.

Suspended solids input data from the estuary suggest an increase from 3581 to 5008 tonnes/year for Balance of Catchment (Table 2.3). It is considered that despite this 30% increase, sedimentation rates will probably remain at a few millimetres/annum for the bulk of the estuary, because this sediment enters the estuary at points well spread throughout the system.

Lateral migrations of the channels in the upper harbour resulting from sedimentation are expected to be only minor as in the past. This process should be clearly differentiated from vertical erosion and accretion in the estuary because lateral channel migration away from a shoreline might suggest to an observer that the area is in a depositional phase, whereas in fact the net overall change, i.e., deposition on one side and erosion on the other, may be zero. Surveys are necessary to assess such changes since casual visual observations and memory can be very subjective and misleading.

<u>Lucas Creek</u>
Changing catchment use will alter the rate and location of sediment deposition.

Urbanisation in the Albany Basin will more than double sediment input to 6698 tonnes/year (Table 2.3). For this reason Lucas Creek will show the most marked change in sedimentation patterns of any part of the Upper Waitemata Harbour. Increased sediment input is likely to result in an increase in sedimentation rate and sediment build-up; the precise amount can only be roughly estimated.

In the neighbouring Hellyers Creek for instance catchment urbanisation may have been the cause of locally increased sedimentation rates in the order of 6 mm/year (Fig. 2.12). In the nearby Wairau Creek catchment urbanisation was accompanied by an increase in the size and frequency of flood events and suspended sediment runoff. This caused severe siltation problems in the Milford Marina receiving waters (Williams 1976, Beca Carter Hollings and Ferner Limited 1978), and seriously reduced the usefulness of the facility because of insufficient water depth (Plate 4.1).

A crude estimate of the maximum potential rate of deposition in Lucas Creek due to runoff from the Lucas and Oteha Streams under urban development can be made by considering the sediment runoff data for the Wairau catchment and rates of deposition in its receiving basin, i.e., Milford Marina. Assume that the Lucas and Wairau catchments will generate similar amounts of sediment runoff per unit area. At its peak in 1976, sediment deposition in the Marina averaged 7300 m^3 per year, and over 1977-80 this reduced to 2500 m^3 per year (Takapuna City Council pers. comm.). If the larger rate is scaled to take into account the difference in catchment areas between the Lucas and Oteha Stream catchments (18.39 km^2) and the Wairau Creek catchment (11.4 km^2) and the difference in depositional basin ratios between the Lucas Creek (111.5 ha of tidal flat area) and Wairau Creek (2.7 ha marina) then the total mass transport to Lucas Creek will be :

$$\frac{7300 \times 18.39}{11.4} = 11766 \text{ m}^3/\text{year}$$

Sedimentation rate in Lucas Creek estuary will be

$$\frac{11766}{111.5 \times 10000} = 0.010 \text{ m/year}$$

In other words if the Lucas and Oteha Stream catchments were to undergo a similar style and pace of development to that of the Wairau Creek they would contribute 10 mm/annum of sediment to the tidal flat areas.

This should be regarded as a crude but absolute maximum rate for Lucas Creek sediment deposition because the geometry of the two depositional basins is quite different, i.e., the Milford Marina is a very special case because ponding of waters by the weir at the mouth, the presence of keel boats and the carpark/break-water at the entrance all act to reduce velocities and thus induce sediment deposition. It is considered that half of the sediment entering the Marina is deposited, the rest passes out to sea (Beca Carter Ferner and Hollings 1978). It is anticipated that a large fraction of input sediments will pass from Lucas Creek to the lower Waitemata Harbour because the geometry of the system is more conducive to flushing.

Historical bathymetric data suggest that over the last 130 years there has been zero sedimentation or erosion in the main body of Lucas Creek, despite major catchment use change (Fig. 2.11). Pollen changes in the sediment column support this because in most parts of the system, the last 500 years or so of stratigraphic record is compressed into the few topmost centimetres. In areas where the sedimentation rate is probably a maximum, the recorded rate is 3 mm/year over the last 140 years (Fig. 2.10). Contemporary rates of sediment deposition calculated from only very short term suspended sediment input records suggest a 2 mm/year maximum - the actual rate is probably less than half this figure since much of the input sediment is considered to be flushed to the lower harbour. By the year 2000 suspended solids input is predicted to double to 6698 tonnes (Table 2.3) i.e., the average net sedimentation rate would increase from 2 to 4 mm/year maximum if all input sediment was deposited.

The sites where deposition will occur in Lucas Creek are easier to predict than the amount of sediment that will be deposited.

Deposition will be concentrated in those areas of low environmental energy such as the present tidal flats and mangrove embayments as at present. However, higher discharge (but similar volumes) will extend the limit of freshwater influence further down the estuary resulting in sedimentation maxima nearer the mouth for comparable pre-urbanisation storm events. Sedimentation would be expected to take place in the vicinity of L6 and L7 (Fig. 2.4) and downstream of L10, particularly in the Te Wharau delta area (L12 to L15) because channel widening will cause velocities to drop off resulting in sediment deposition. In the present system a topographic high at L12 impedes ebb tide drainage of upstream waters and flushing of the system. Further sedimentation in the vicinity of L12 will accentuate this problem. Sedimentation could result in lateral migration of the channel in the wide estuarine reach between L11 and L15. Further upstream the channel is too restricted by bedrock to move appreciably. These effects will be most pronounced during the development phase of urbanisation when sediment input is large.

Higher freshwater discharge will increase the frequency and magnitude of intermittent sediment stripping events in the reaches of estuary upstream of L7 and will result in very low or negative sedimentation rates. Stripping of the upper layers of sediment and channel bank scour will continue during both the constructional and completed stages of urbanisation. In the Wairau Creek estuary for example floods have caused severe bank erosion and channel scour in the upper reaches (Plate 4.2).

The Lucas Creek entrance reach mooring area extends 900 m upstream of the mouth, and is identified as a site where excessive sedimentation could seriously impair a facility used by both the public and the Salthouse boat building industry. At August 1982 there were 83 moorings registered by the Harbour Board in Lucas Creek, at which launches up to 15 metres and yachts up to 13 metres were moored. Conditions for mooring and manoeuvring craft, particularly at low water, are marginal. Even at higher stages of the tide low water clarity makes it easy to go aground on the intertidal flats. Further Harbour Board approvals for moorings in the area are dependent on the size of the craft. Any sediment build-up in this area and increasing turbidity, can only make worse the already marginal mooring facilities and navigational conditions.

It is highly likely that the particle size and nature of sediment entering Lucas Creek will change with urbanisation.

Observations in Auckland urban estuaries (e.g. Milford Marina, Tamaki estuary) suggests that urbanisation may result in a relative increase in the quantity of the larger size fractions of material entering the estuary, such as gravel from drives and roads (Plate 4.3), although overall the volume of this material will be small. It is preferable that this material be kept from entering Lucas Creek because under normal conditions, channel tidal currents are too weak to rework material of pebble size (> 4 mm) and larger. Finer sandy input sediments are less likely to be problem because spring tide currents at most channel locations are adequate to rework and transport this material as bed load.

Field examination of Aucklands urbanised estuaries shows that a potentially serious problem is the accumulation of urban debris such as construction and roading metal, concrete, tree and shrub debris, glass, metal, wooden and plastic objects in the system which detracts from the estuaries visual appearance. Entrappment at source is the only effective solution to this problem.

In summary, it is anticipated that sedimentation effects accompanying land use change in the Upper Waitemata Harbour will be largely localised in Lucas Creek and that, apart from temporal increases in water turbidity, sediment deposition will be largely undetectable elsewhere.

4.2 SEDIMENT NUTRIENTS

Too little is known about the processes of nutrient exchange between the estuarine sediments and estuarine waters to predict the quantitative effect that changes in river input and estuarine water nutrient levels accompanying land use change, are likely to have on estuarine sediment nutrients. Nor did this study attempt to address this complex research problem. However, our knowledge of the sedimentology and existing nutrient distribution patterns enables us to assess the susceptibility of the sediments to nutrient enrichment and pinpoint likely areas and times of nutrient build-up.

The very fine grained nature and the clay mineralogy of surficial Upper Waitemata Harbour sediments (Figs. 2.13 and 3.6) indicates that the potential of the sediments to sorb nutrients and possibly organic and inorganic pollutants is high.

In the Upper Waitemata Harbour locations for potential nutrient build-up are those poorly flushed areas of the western harbour main axis and the Brighams, Rangitopuni, Rarawaru and Paremoremo Creeks, where nutrients are the highest at present. In comparison, nutrient levels in surficial sediments of Lucas, Hellyers and Waiarohia Creeks, the lower channel areas of the other creeks, and the eastern main axis of the Upper Harbour are likely to be less because they are near the harbour entrance where tidal exchange is larger.

In particular nutrient accumulation generally would be expected to be greatest where fine grained sediments build-up in areas, of low environmental energy high on the intertidal areas particularly the mangrove embayments. Sediments in the channels are less likely to become nutrient enriched because of their coarser grain size and more importantly because of frequent reworking and flushing by tidal currents. High freshwater inputs during floods that periodically strip surficial sediments in the narrow inlet headwaters, particularly in the Rangitopuni and Lucas Creek, would serve to flush nutrient enriched sediment.

Nutrient enrichment in surficial sediments will be its greatest in spring and summer as a function of natural fluctuations.

It is difficult to make quantitative comment on the present level of nutrient enrichment of Upper Waitemata Harbour sediments, as there is no universally recognised "index" to gauge the trophic status of estuarine sediments. Such indices are difficult to "construct" as plant growth is limited by other factors beside nutrient levels, including substrate type, water temperature and light availability.

4.3 CHANGE IN WATERWAY USE AND ENGINEERING WORKS

Engineering activities such as causeway construction, reclamations and other developments that act to alter tidal flow and/or wave climate will alter environmental energy and change sediment distribution patterns. Deposition in the vicinity of such developments is likely to be initially rapid. The present distribution patterns of sediments in the estuary demonstrate that if environmental energy is reduced sediments will accumulate and grain size will be reduced. For instance, the construction of the causeway between Herald Island and the mainland blocked the tidal flow and reduced wave action through the area resulting in rapid sedimentation of muds and mangrove expansion (Thompson and Gregory 1973). The deposition is supported by historical records (Fig. 2.11).

Dredging and disposal of tailings in the Upper Waitemata Harbour associated with maintenance and development of marinas, navigational channels and other facilities poses special problems because the sediments are fine grained and difficult to handle.

Changes in the submarine topography due to removal (dredging) or deposition (disposal) of material can cause changes in the hydraulic regime of an area with effects on sedimentation patterns and biological habitat. Increases in turbidity with its ecological impacts are probably the greater concern because of the abundance of fine grained sediments in the upper harbour, even though most species present in an estuary are likely to be normally adapted to relatively high levels of turbidity, albeit temporary.

A cross channel cut made in September - October 1980 by the Takapuna City Council for the Paremoremo Prison water supply pipeline (Plate 4.4) showed the dredged channel section to be surprisingly stable in sub-aerial exposure. However, dredge spoil stock piled on the tidal flats slumped and spread. Turbidity caused by the dredging operation was very short lived and restricted to one or two tidal cycles (C Glenfield pers. comm.). The dredging experience in Lucas Creek suggests that only longer term and larger scale operations in the Upper Harbour need cause concern.

Careful planning of dredge cuts and disposal sites can minimise impact and avoid costly maintenance dredging. The impact of dredging operations can be lessened by regulatory controls that relate to the total resource and the incremental effect the proposed action will cause. These may include choice of dredging equipment, land disposal of spoil, use of silt curtains, restrictions on upper limit of turbidity levels, or banning dredging during periods of high biological productivity in spring and summer (seasonal dredging moratoriums).

The upper harbour is shallow, sediments are fine grained and cause turbidity, and tidal flows are generally weak. For these reasons considerations should be given to prohibiting the disposal of dredge spoil in the upper harbour and alternative land or ocean sites utilised.

Increasing boat traffic in the estuary may increase internal sediment generation in the estuary due to bank and tidal flat erosion caused by wake wash.

In the absence of a more sophisticated model the channel cross sectional area - tidal prism (A - P) relationships developed for the Upper Waitemata Harbour and Lucas Creek provide a useful engineering tool for both estimating tidal discharge in Auckland inlets, and for predicting the relative sensitivity of estuaries to engineering works that result in changes in channel geometry and tidal prism. If the tidal compartment is decreased (reclamation) or increased (dredging) through engineering works in the intertidal zone, the estuary will respond by silting or scouring its bed respectively, resulting in a change in channel cross section area by an amount that can be predicted from Figs. 2.15 and 3.15. Similarly, a decrease in channel cross sectional area due to barrage construction for jetties or causeways will cause a corresponding reduction in tidal prism resulting in sedimentation upstream of the works.

There are a number of estuaries in the Auckland area where barrage works for road or railways have reduced the channel cross sectional area, namely, the Whau and Waterview Inlets of the western Waitemata Harbour and the Whakatapatapa and Judges Bay Inlets on Auckland's waterfront drive. These inlets lie well below the A-P relationship line for Auckland estuaries (Fig. 2.15) indicating their entrances are too small for the tidal prisms. The continued increase in Whau Inlet entrance dimensions that has followed the 1952 causeway construction

(Hume in prep) supports this hypothesis.

The relationships derived for 3 segments of Lucas Creek (Fig. 3.15) indicate that different parts of the system will respond at different rates to imposed changes. For instance, the lesser gradient of the line for the entrance reach (L16 - L18) indicates relatively large changes in tidal prism (e.g. dredging of intertidal areas) will cause only small adjustments in channel cross sectional areas. In comparison the steep line for the central reach (L8 - L12) indicates the channel cross section geometry will respond a relatively large amount to dredging or reclamation in the intertidal zone.

The Upper Waitemata Habour has a potential for active sedimentation in the entrance at Hobsonville (by 4% of the cross sectional area) and/or for an increase in the upper harbour tidal prism (by approximately 20%) (Fig. 2.15). Engineering works in the Upper Waitemata Harbour that alter channel cross sectional areas, or involve tidal prism changes through dredging and reclamation, should be planned with the equilibrium relationship (Fig. 2.15) in mind. Reclamations, in particular, can alter estuarine equilibrium and should be discouraged. The sum effect of a number of small reclamations is the same as that for a single large one of the same area. Of course the intertidal areas are ecologically important to the whole of the Waitemata Harbour (Upper Waitemata Harbour Catchment Study 1983b), so proposals for engineering works must also consider this fact.

CHAPTER 5 : SUMMARY AND CONCLUSIONS

5.1 UPPER WAITEMATA HARBOUR SEDIMENTS

Studies of subsurface sediments show that sedimentation began in the Upper Waitemata Harbour estuary some 6500 yr BP, and since this time the nature of input sediment, sedimentation rate and environmental energy has fluctuated markedly in response to changing freshwater and sediment input, sea level and catchment use. Pollen analysis of sediments show changes in vegetation attributed to the arrival of the Polynesian at about 530 yr BP, followed by European settlement and land development beginning at about 110 yr BP (about 1841). The 0.8 mm/yr sedimentation rate recorded just inside entrance of Lucas Creek, associated with the Polynesian phase, quadrupled during the subsequent European phase, perhaps largely as a result of logging and gum digging activities. Since 1854 sedimentation has been most rapid in the western part of the Upper Waitemata Harbour main axis, and in the middle and lower reaches of the tidal creeks. Lucas Creek, however, has experienced zero sedimentation or net erosion perhaps as a result of its greater flushing capacity. Zero sedimentation in the upper reaches of the harbours tidal arms results from flushing associated with flood events.

Today, Upper Waitemata Harbour sediments derive largely from streams during flood events and the dominant input material is fine sand to clay size. Surficial sediments of the Upper Waitemata Harbour reflect this input being largely very fine grained sandy muds and muddy sands. The clay fraction contains largely poorly crystalline illite, smectite and kaolinite.

Sedimentation patterns in the estuary are controlled primarily by the tides. The finest sediments accumulate on the upper tidal flats and in the mangroved embayments where currents are weak. Coarse sands and a few areas of shell gravels concentrate locally near the entrances of the tidal creeks, on channel flanks and in the Herald Island narrows where currents are strong. Overall, sediments fine toward the western end of the harbour where flushing is poorer. In the main body of the estuary, freshwater inflow has little effect on sedimentation except during floods, when large quantities of suspended solids entering the estuary may result in average net sediment accumulation of up to 3 mm/yr. In the upper reaches of the tidal creeks however, floodwater flows may erode surficial sediments.

Comparison of the channel cross sectional area (A) and tidal prism (P) relationship for the Upper Waitemata Harbour with that derived for Auckland estuaries suggests the upper harbour is not in sedimentary equilibrium, and that the inlet is likely to be undergoing changes in flow and sedimentation patterns leading to an increase in tidal prism and decrease in cross sectional area of the channel (below mean discharge level) or sedimentation at the Hobsonville entrance.

Nutrient levels in the Upper Waitemata Harbour surficial sediments average 2.08% for total organic carbon, 1300 mg.kg for total Kjeldahl nitrogen and 363 mg.kg for total phosphorus. TOC, TKN and TP show no clear trends down the tidal creeks but are higher in the Rangitopuni, Brighams, Rarawaru and Paremoremo creeks, than in the eastern Lucas, Hellyers and Waiarohia inlets. TOC and TKN are higher in the western main axis than in the east. The higher nutrients in the west coincides with poorer flushing in these areas. ROC and TKN concentration in sediments increase markedly with decreasing grain size. TP shows no such trend. Fine grained intertidal samples in Lucas Creek contained on average 50% more TKN, TP and ROC than a coarser textured sample from an adjacent channel area. Marked increases in sediment nutrients, particularly TKN and ROC were found to occur in spring and summer.

In Lucas Creek estuarine morphology and tidal prism are described by a formula which relate channel cross sectional area (A) and tidal prism (P) for three reaches in the inlet which are segmented by bedrock structure. This fact and the large tidal prism to total volume ratio suggests the patterns of sedimentation and erosion, and overall morphological stability are controlled primarily by current flows generated by the semi-diurnal tides. Weak tidal currents about high tide allow fine grained sediments to accumulate primarily on the tidal flats, then consolidate during subaerial exposure at low tide.

It is probable that neap tides concur with net depositon, and spring tides, and associated strong tidal currents, with net channel scour and reshaping.

The "tidal sedimentation pattern" is disturbed by random pulses of freshwater and considerable sediment input associated with floods. In 1980 80% of the annual sediment input to Lucas Creek by the Oteha Stream occurred during storm events that make up approximately 2% of the flow duration time. The maximum estuary-wide average sedimentation rate due to these events is estimated as having been about 2 mm. The winter coarsening and summer fining of surficial sediments is considered to be largely a result of coarsening sediment input associated with more frequent and larger winter stream inflows; and not due to sorting *in situ* by wave action.

During floods, stream flows erode sediment from the narrow upper reaches of the tidal creeks and, along with the dominantly suspension load river input, transport and redeposit sediment in the lower estuarine reaches where velocities lessen in response to increasing waterway width and decreasing freshwater influence, and/or pass through the entrance to the middle reaches of the Waitemata Harbour. It is probable that a large proportion of sediment entering Lucas Creek during storm events is flushed out the Hobsonville entrance to the middle harbour. After floods more moderate tidal forces then gradually restore the system to a "tidal equilibrium". Once deposited the muddy cohesive estuarine sediments are resistant to reworking by weak tidal currents except under peak spring tide flows.

5.2 CATCHMENT AND ESTUARY USE CHANGE, ENVIRONMENTAL CONSEQUENCES AND REMEDIES

CATCHMENT USE CHANGE

In general, catchment use change in the Upper Waitemata Harbour will increase the stream flood frequency and magnitude (Smith 1983), and the quantity of sediment nutrients carried by the streams (van Roon 1983).

The Upper Harbour will continue to experience high turbidity during and for short periods after, storm events. Sediment depositon will continue to be largely fine grained, occur largely in areas of low environmental energy in embayments high on the tidal flats and in the central and lower reaches of the tidal creeks. Because the sediment sources are spread around the harbour the net average sedimentation rate is likely to remain low. The most marked change in Upper Waitemata Harbour sedimentation patterns will result from increasing flood water and sediment runoff accompanying catchment urbanisation in Lucas tidal Creek, and to a far lesser extent forest harvesting in the Rangitopuni. The extent of change however, will be very dependant on the methods and pace of land use change.

In Lucas Creek sediment will be mainly deposited on the tidal flats in the middle wider reaches. Sedimentation will probably increase during urbanisation to a net average of several millimetres per annum. Once the catchment is urbanised sediment input will drop. Much of the fine grained sediment entering Lucas Creek will be fine grained suspended load and will continue to be flushed to the lower Waitemata Harbour. Very coarse sediment resulting from urban development (e.g. roading and construction gravels) are likely to remain trapped in the estuary. Increasing sedimentation can only be effectively minimised by action at the source. Catchment development should utilise engineering methods that minimise surface runoff and soil erosion to avoid large injections of sediment in short periods of time e.g. develop small areas at a time, grass bare areas, carry out construction during periods of low storm occurrence and use sediment traps (large volumes of water associated with suspended material make silt detention only partially successful). Sediment erosion in the upper reaches of the Lucas Creek resulting from increasing flood frequency and magnitude can be minimised by reducing the impervious area of developed catchment, developing flood detention areas and soakage systems.

Nutrient enrichment in surficial sediments will be greatest where fine grained sediments accumulate in areas of low environmental energy and flushing is poor, i.e., in the upper reaches of the estuary and high on the tidal flats in mangroved embayments. Nutrient build-ups will be greatest in summer. Solid wastes in the form of urban debris (wood, plastic containers etc) are a probable serious consequence of urbanisation as they will wash into Lucas Creek where they will litter the low energy zones, particularly the mangrove areas. Sediment stripping in the upper reaches of the tidal creeks (particularly the Lucas and Rangitopuni which have high freshwater input) will erode sediments and minimise pollutant and nutrient build-up. However, in catchments where flood waters may be impounded for irrigation purposes (e.g., Brighams) sediment stripping and periodic flushing by floods would be lessened.

ESTUARY USE CHANGE

Estuary use change can alter environmental energy in parts of the system, and alter tidal patterns and flows, all of which can bring about sediment redistribution.

Increasing power boat traffic will increase boat wake wave erosion of the shoreline in upper narrow waterways, particularly at high tide, as well as increase turbidity (short term). The effect will be minor unless traffic increases considerably and larger displacement hull craft become more common. The effect can be minimised by limiting boat speeds.

Siltation and/or scour will occur in the vicinity of engineering structures that impede tidal flow. Structures should be aligned with flow or piled to allow flow beneath. Embankments and causeway construction should take into consideration channel cross sectional area - tidal prism relationships; otherwise reduction in tidal prism will lead to siltation upstream.

Reclamations in the intertidal zone result in a reduction in the tidal compartment with consequential decreases in tidal velocity and the capacity of the system to flush sediment and pollutants. Net channel cross sectional area changes and scour of the intertidal area resulting from reclamations can be predicted for the Upper Waitemata Harbour and Lucas Creek from Figs. 2.15 and 3.15 respectively. Reclamations in particular, are likely to alter estuarine stability and flushing and should be discouraged. Several small reclamations can have a similar effect to a single large one. If reclamations are constructed they should not obstruct tidal flow patterns otherwise local sedimentation and scour will result.

Dredging above the low tide level will increase the tidal prism and result in greater tidal flushing. The effect of dredging in the Upper Waitemata Habour and Lucas Creek can be predicted from Figs. 2.15 and 3.15 respectively. Fig. 2.15 suggests estuarine stability of the upper harbour would be increased by dredging in the intertidal zone (increase tidal prism by up to 20%). Dredging will result in increased turbidity that will be short term, small scale and local. Dredge tailings should not be disposed of in the estuary, but rather as bunded land fill or outside the harbour.

5.3 RECOMMENDATIONS FOR FUTURE WORK

Future land and estuary use change are likely to alter patterns of sediment distribution, scour and siltation, sediment texture, nutrient and pollutant levels in surficial sediments, and estuarine morphological stability to varying degrees.

It is important that a monitoring program be set up to quantitatively record changes in these parameters, particularly over the period of most intense land use change and development, and in those areas where problems are anticipated. Without such a program objective evaluation of problems will give way to lengthy subjective debate. Furthermore, the considerable effort and resources used in the Upper Waitemata Harbour study should be capitalised on by recording the effects of any future land and estuary use change on the estuary to check conclusions presented in this report.

Baseline data for Lucas Creek presented in Fry and Hume (1983) together with this report are suitable for setting up a monitoring program whilst the quantitative descriptions of sampling and analysis procedures, and short term (seasonal) variations in sediment texture and nutrients provide a good basis for planning harbour wide surveys. Baseline data for the Upper Waitemata Harbour is available from this report.

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PLATES

Plate 1.1 : The Upper Waitemata Harbour estuary looking east toward Herald Island and the Greenhithe Bridge cf Fig. 1.1). The Rangitopuni and Brighams Creeks run left to right in the foreground respectively. Photo taken on 25 May 1979 at spring low tide.

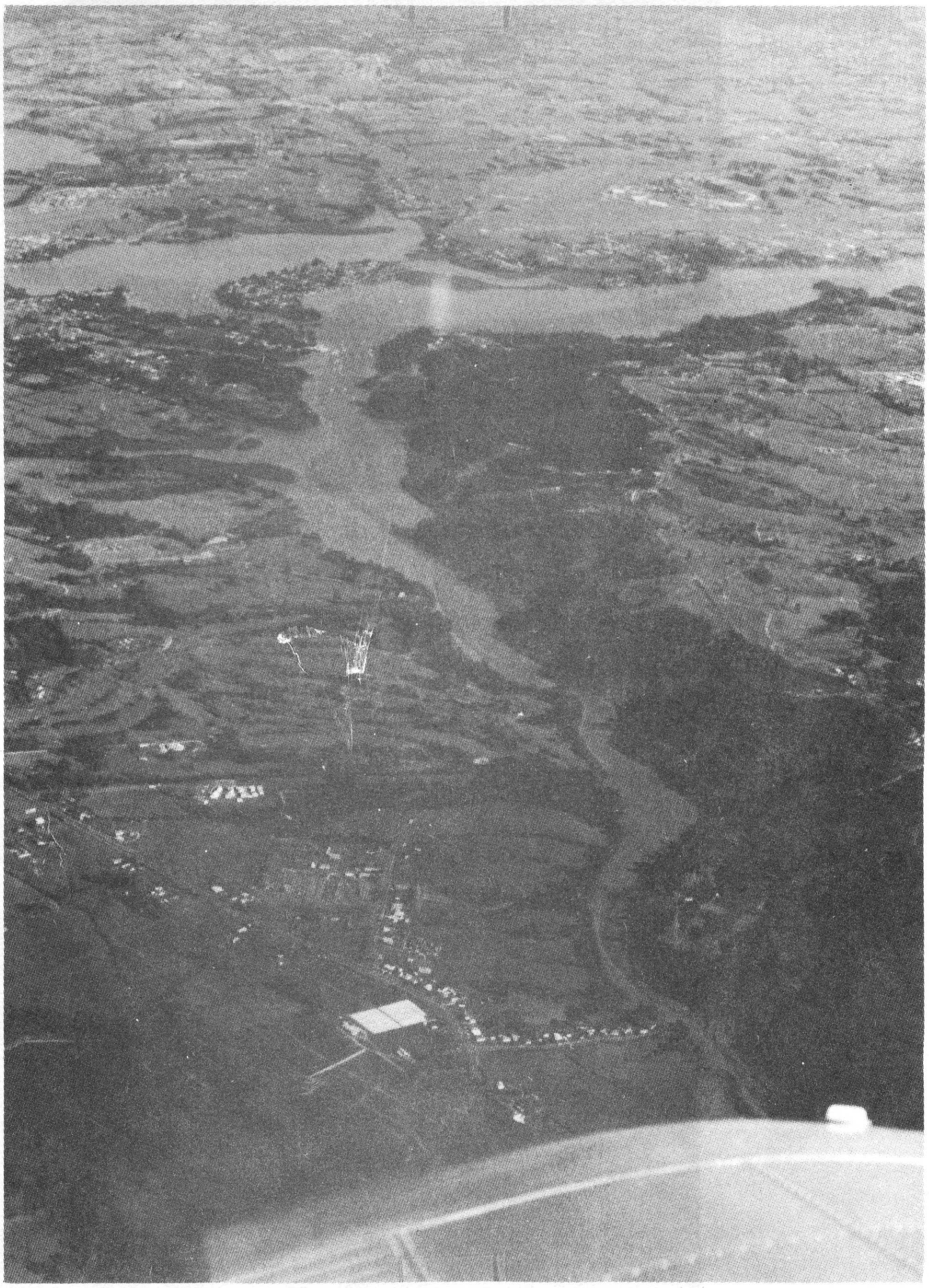

Plate 3.1 : Lucas Creek estuary looking southwest toward Herald Island and the Waiarohia Estuary (cf Fig. 1.1). Wharf Road and section L5 lie in the immediate foreground, the Te Wharau Creek in the upper centre, beyond which lies the entrance reach and the mooring area. Photo taken on 10 July 1979 at spring low tide.

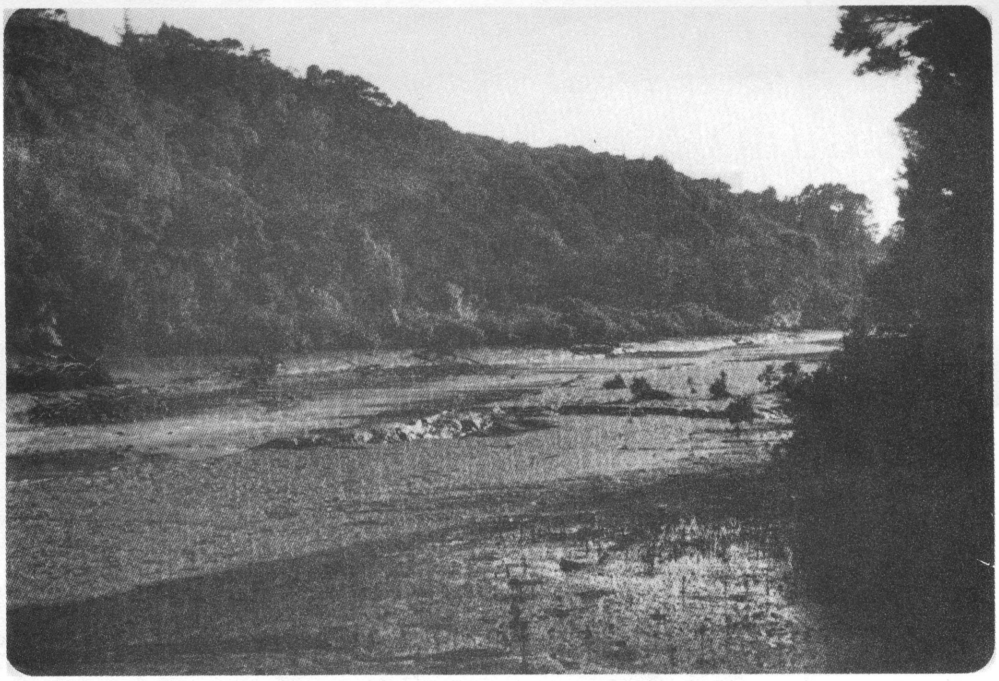

Plate 3.2 : Rock bars upstream of L5 at Wharf Road Lucas Creek. The main channel is flanked by elevated tidal flats, cut by incised drainage channels, and mangrove shrubs. Note the bush debris left on the far bank after the Telethon storm of 30 June 1979. Photo taken on 5 July 1979.

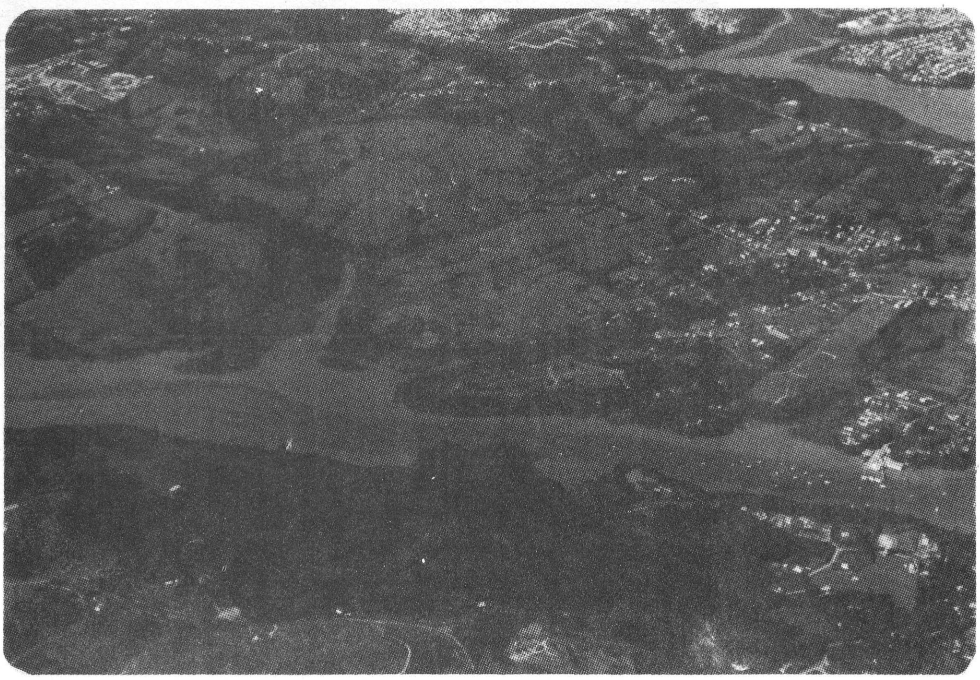

Plate 3.3 : Aerial oblique of the Te Wharau Creek delta area (left of centre) and entrance reach of Lucas Creek. Note the extensive mangrove development and shoals in the Te Wharau area and the subtidal bar that separates ebb and flood tide flows at the entrance to Lucas Creek (Photo taken on 25 May 1979 at spring low tide).

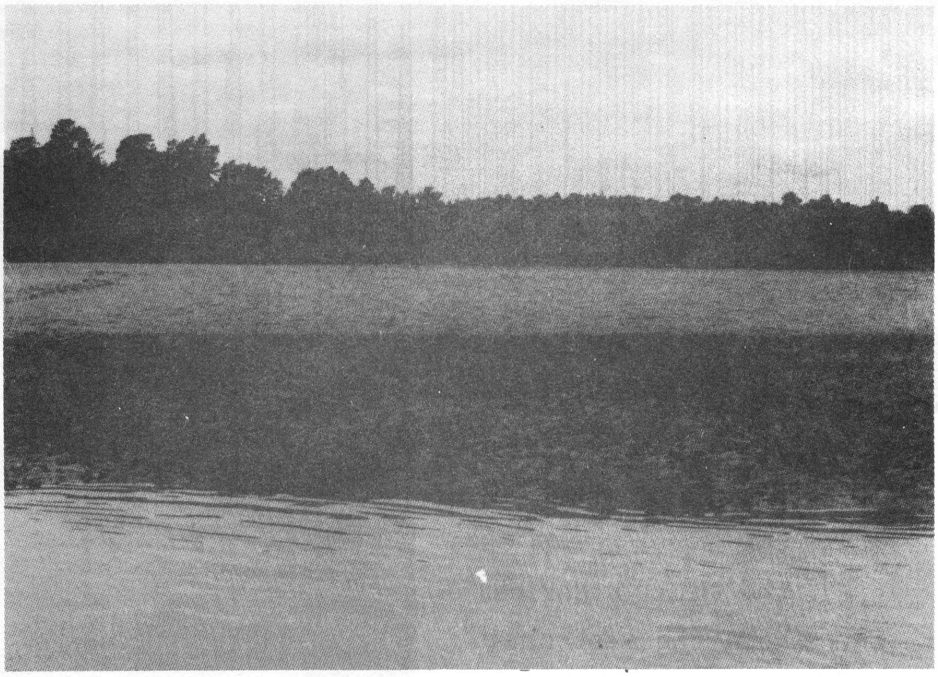

Plate 3.4 : Lag gravels formed from shell debris exposed on the eastern channel flank in the Te Wharau area, Lucas Creek. Photo looks east along L14 (18 April 1980, tide level about 0.1 m CD).

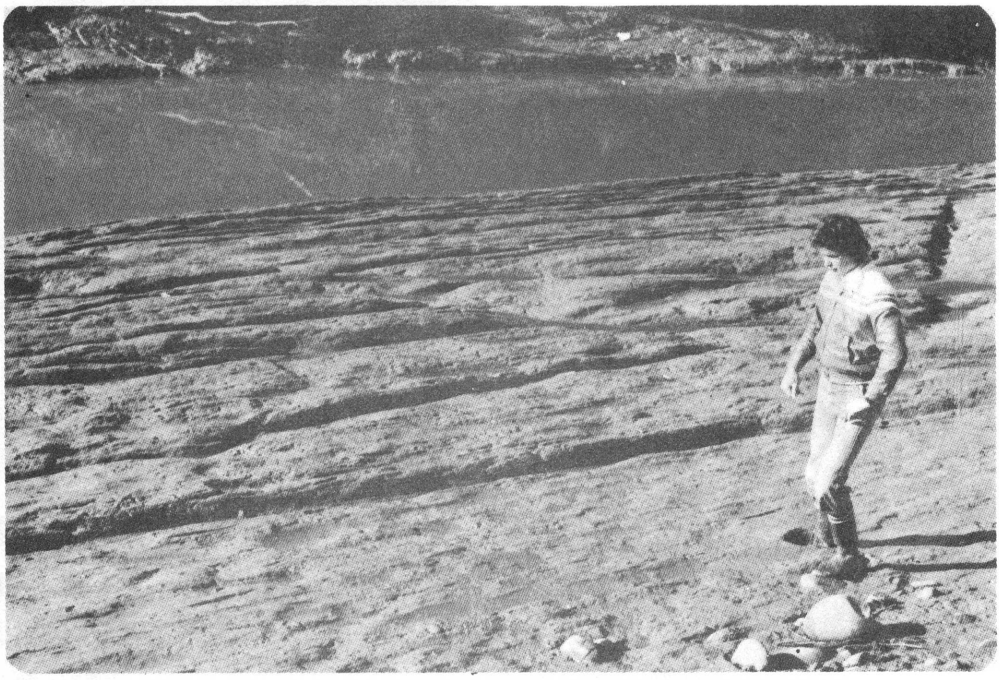

Plate 3.5 : Scour trails in muddy tidal flat sediments of Lucas Creek between L3 and L4 (Fig. 2.4). The grooves were cut when flood debris (trees and shrubs) was transported by flood waters down the creek during the Telethon storm of 30 June 1979. Photo taken on 5 July 1979.

Plate 4.1 : Build-up of muddy sediments in the berthage areas on the western side of the Milford Marina. Note the keel drag marks and holes scoured by propellor wash. Photo taken on 2 May 1980.

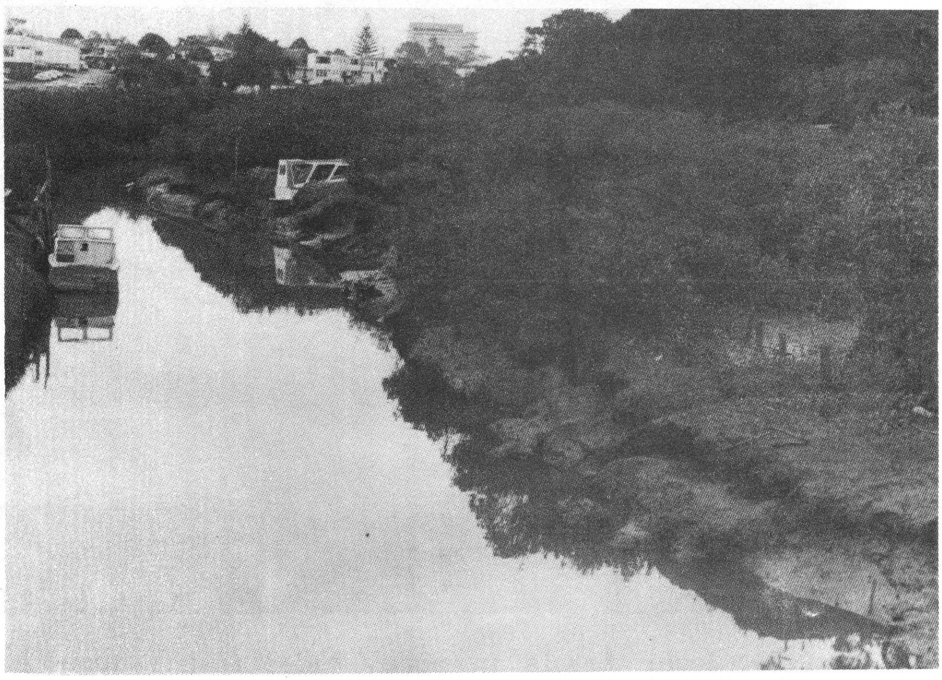

Plate 4.2 : Mangrove area between Sheriff, and Inga Road bridges in Wairau Creek estuary. Note the deep central channel and the eroded and collapsed channel banks quite atypical of a natural estuary. Photo taken on 2 May 1980.

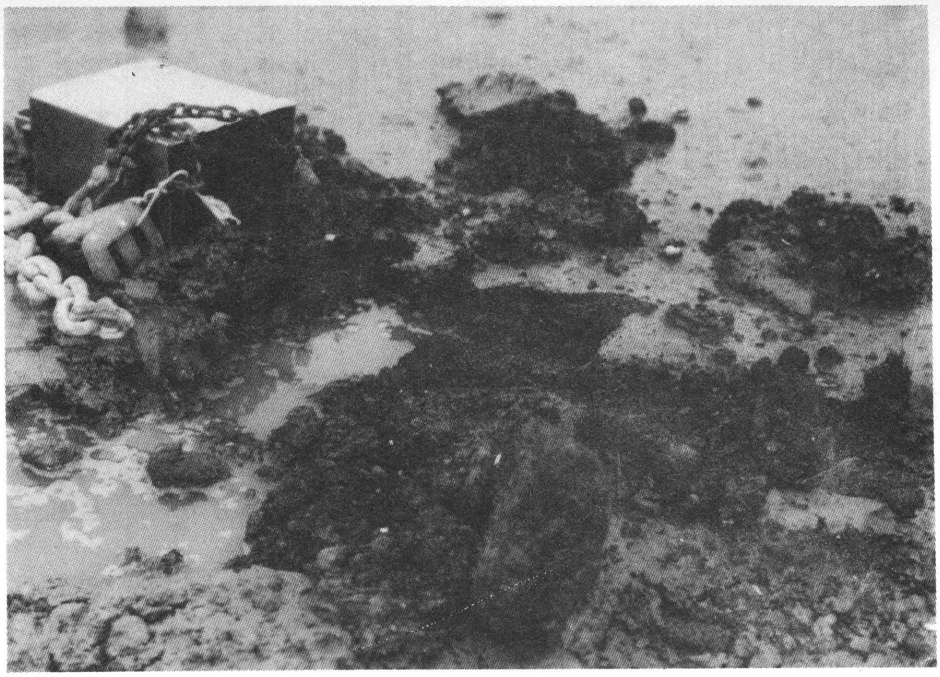

Plate 4.3 : Poorly sorted sands, gravels and cobbles dumped by flood waters at the Inga Road Bridge entrance to Milford Marina. The thin (1-2 cm) muddy surface layer represents low freshwater inflow deposits. Sediment dredge is 15 cm in width. (Photo taken 2 May 1980).

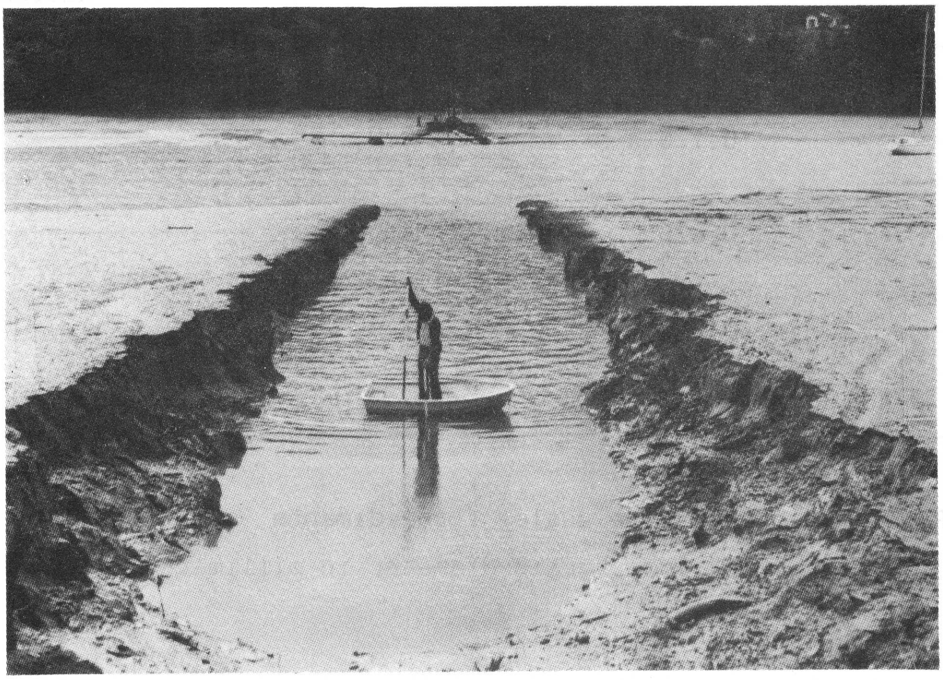

Plate 4.4 : Looking northwest along the trench cut for Paremoremo water supply pipeline across Lucas Creek, midway between L17 and L18. The trench was 2.5-3 metres below the sediment surface in places.

Millimetres	Phi (φ)	Wentworth Size Class	
		Boulder	G R A V E L
256	-8		
		Cobble	
64	-6		
		Pebble	
4	-2		
		Granule	
2	-1		
		Very coarse sand	S A N D
1.0	0.0		
		Coarse sand	
0.5	1.0		
		Medium sand	
0.25	2.0		
		Fine sand	
0.125	3.0		
		Very fine sand	
0.625	4.0		
		Silt	M U D
0.0039	8.0		
		Clay	

APPENDIX I. Grain size scales for sediments
$\varphi = -\log_2$ (grain diameter in millimeters).

SEDIMENT TEXTURE	
<u>GRAVEL</u>	
mG	muddy Gravel
mfsG	muddy fine sandy Gravel
G	Gravel
<u>SAND</u>	
sgmmS	slightly gravelly muddy medium Sand
gmmS	gravelly muddy medium Sand
mmS	muddy medium Sand
gfS	gravelly fine Sand
gvfS	gravelly very fine Sand
gmfs	gravelly muddy fine Sand
sgmfS	slightly gravelly muddy fine Sand
gmvfS	gravelly muddy very fine Sand
sgmvfS	slightly gravelly muddy very fine Sand
mfS	muddy fine Sand
mvfS	muddy very fine Sand
S	Sand
<u>MUD</u>	
gfsM	gravelly fine sandy Mud
gvfsM	gravelly very fine sandy Mud
sgvfsM	slightly gravelly very fine sandy Mud
sgM	slightly gravelly Mud
vfsM	very fine sandy Mud
M	Mud

APPENDIX II. Descriptive terms applied to mixtures of sand, gravel and mud. The major textural class is defined by the capital letter (c.f. Appendix I).