PART SIX

SUMMARY AND SYNTHESIS

Summary history of the Avon-Heathcote estuary

The AHE is on a coastal plain which consists of Late Quaternary terrestrial and estuarine gravels, sands, peats and mud (Part One; Figure 1). The estuary probably formed between 1 000 and 2 000 yBP. When the first settlers arrived, in 1850, the area which is now Christchurch City was predominantly swamp and marsh, separated from the sea by a belt of dunes. Early urbanisation probably led to a rapid increase in the supply of fine sediment to the estuary, particularly during the period 1850-1875, when little effective drainage work was undertaken but the population grew from a few hundred to more than 10 600 people. The establishment of the Christchurch Drainage Board and a subsequent burst of drainlaying activity meant that by 1900 54 km of sewage and stormwater pipes were laid, and the quality of surface water (and public health) improved as a result. Increasing impervious cover (mainly roofs and roads) and more efficient drainage resulted in increasing volumes of storm runoff, and a reduction in the runoff lag time. In combination with a decreasing availability of erodible material, these effects caused a steep decline in the supply of sediment to the estuary.

Urbanisation and drainage modifications in the catchment of the AHE resulted in an accumulation of sediment, and a decrease in the tidal compartment. Estimates of post-European changes in the volume of the tidal compartment show that during the first 50 years it decreased by about 30% (Part One; Figure 3). However, shortly after the CDB was established, this trend slowed, then reversed, and the tidal compartment has since increased to about 30% more than its 1850 volume. The two trends were probably exponential (Figure 4). The first was due to early urbanisation and increased sediment yields; the second was probably due to a reduced sediment supply and radical changes to the hydraulics of the freshwater catchment of the estuary.

A reconstruction of historical changes that have occurred around the inlet of the estuary since 1850, based on a series of maps made at 20-30 year intervals (Figure 5), shows that these changes occurred in three phases; from 1850 to about 1925 there was little change; from 1925 to 1955 winter storms precipitated episodic changes which resulted in a 500 m northwards migration of the seaward section of the principal subtidal channel, a southwards migration of the landwards section into Moncks Bay, sympathetic adjustments of the end of Brighton Spit, erosion of sand from Sumner Beach, and deposition of sand to form a new beach at Clifton. From 1955 to the present the new configuration has changed little.

The changes which occurred after 1925 were in-phase with changes in the tidal compartment, and significant changes only occurred when the tidal compartment increased above the 1850 (pre-European) volume. Changes at the outlet and to the volume of the tidal compartment have since occurred at parallel rates. The inlet has adjusted to the larger volumes of water flowing through it, and has adopted a different configuration as a direct result of the exponential response of the tidal compartment of the estuary to changes in sediment yields and runoff caused by the development of Christchurch City.

The belief that the AHE has been changed by man's activities is fully justified. The changes which have occurred have had an exaggerated effect in this estuary because it is small and microtidal, and because the freshwater catchment of the estuary is so thoroughly dominated by the Christchurch urban area. It is clear from Part One that physical pollution of the sort that has occurred in this estuary is not irreversible. Generalising from the results summarised above, the indication is that estuaries are capable of adjusting and readjusting quickly to changes in local sediment and water budgets. Altered runoff characteristics may be the major agents of physical pollution in urban watercourses, and in nearby water bodies.

There have been some highly visible and costly consequences of the impact of Christchurch City on the AHE - for example the alterations to the inlet area, and the resulting shore protection work at Sumner and in Moncks Bay (Scott, 1955). Inevitably, other changes must also have occurred, especially as a result of large variations in the volume of the tidal compartment - changes in mean salinity, mean water temperature, suspended sediment concentrations, wave characteristics, bottom sediment properties, tidal current velocities, and so on.

A process-response link between changes in the tidal compartment of an estuary and progressive, systematic changes in the configuration of the inlet to the estuary has not been previously reported in the literature. The discovery of such a link may have significant planning and engineering repercussions in areas where inlet changes threaten seaside real estate (as has happened in the Christchurch area - Part One, and as is currently happening in several other coastal areas in New Zealand). If a history of catchment landuse alterations can be reconstructed for an estuary, and especially if historical charts of the inlet are available, reasonably confident predictions of future patterns and rates of change may be possible. For another recent discussion of this subject see Reinson (1977).

Energetics

1. *Wind and waves*. Major conclusions reached after an analysis of the wind climate of the AHE are that effective wind stress is directionally anisotropic, that the east wind is twice as frequent as the south-west wind and four times as frequent as the north-west wind. Maximum effective fetch distances of about 1 800 m are uniformly distributed along the eastern and southern shores of the estuary, and fetch distances increase from north to south along the north-western shore. Width limitations significantly modify the distribution of effective fetch in the Heathcote Basin (Figures 6 to 10).

Because the estuary is shallow, maximum waves have periods of 1.4 s, amplitudes of 30 cm and lengths of 3.5 m. Waves reach this maximum size quickly and relatively close to the start of each fetch, so that downfetch gradients in wave energy are due to increasing wave frequencies. With increasing fetch distances, more low velocity wind events generate waves large enough to interact with the bottom. Because west winds tend to be higher velocity events, downfetch energy gradients are less well developed in areas subject to longfetch westerlies. East winds tend to be lower velocity events, and are more likely to generate downfetch energy gradients.

The application of small amplitude (Airey) wave theory (Part Two) has shown that maximum near bottom orbital velocities under waves in the AHE vary from 10 cm/s in water 1.5 m deep, to 22 cm/s in water 0.5 m deep. The amplitudes of orbital motions increase from 3 to 5 cm during the translation from 1.5 m deep water to 0.5 m deep water. Since near bottom shear stress is a function of both water depth and bottom roughness, and the presence of ripples significantly increases relative roughness values, there are very large differences between shear stresses exerted on the bottom in water 1.5 m deep, where roughness may be very fine sand sized, and in water 0.5 m deep, where ripple sized roughness may occur. Shear stress values increase from 0.5 dynes/cm^2 to 2.0 dynes/cm^2 to 17 dynes/cm^2 as water in the AHE shoals from 1.5 m to 1.0 m to 0.5 m below HWOST, and the large increase from 1.0 m to 0.5 m (almost an order of magnitude) is particularly important.

A refraction analysis (Figure 13) indicates that wave directions are only significantly altered in water shallower than 1.2 m below HWOST in this estuary (where the bottom is above 9.0 m HAD), and that refraction acts to homogenise wave properties. However, in the north and west, and in the Heathcote Basin, the shoaling transformation reduces wave sizes, and effectively produces wave shadows.

2. *Tidal currents*. A review of current velocities measured in the AHE indicates that probable maximum values for different water depths range from 5 to more than 100 cm/s. Near bottom shear stresses, calculated from the quadratic stress law with an assumed drag coefficient (c_{100}) of 3×10^{-3}, vary from less than 0.01 dynes/cm^2 in water shallower than 0.5 m to more than 25 dynes/cm^2 in the deeper intertidal and subtidal channels. Even though these are probably no better than order-of-magnitude estimates, they emphasise the surprising discovery that tidal current shear stress values exceed wave induced shear stresses only on thelowest intertidal flats and in the subtidal channels of this estuary. This is true in spite of the large amounts of kinetic energy contained in the ebbing and flooding tide. These estimates also emphasise that in this estuary, tidal and wind induced shear stress maxima are mutually exclusive and that the area of lowest combined shear stress occurs at intermediate depths, midway between the high water mark and the subtidal channels (Figure 32).

Current generated bedforms, predominantly lingoid and undulatory straight ripples, are only found on lower intertidal flats, in the subtidal channels, and on the flood delta in the AHE. Here tidal velocities reach maximum values of about 60 cm/s. Larger bedforms - megaripples and sand waves - only occur in the inlet area adjacent to the principal subtidal channel, where velocities exceed 80-90 cm/s on both the ebbing and flooding tides (Figure 19).

Threshold criteria indicate that tidal currents which exceed 60 cm/s are capable of entraining very coarse sand and small granules; typical lower intertidal currents of 35 cm/s are capable of entraining very fine sand and silt sized particles.

3. *Wind-driven currents.* The influence of wind entrainment on large scale, cross-estuary, advection of water and suspended solids, and on tidal current velocities, is an unexplored effect in this estuary. Qualitative observations of wind-driven longshore currents and of flooding due to wind setup indicate that wind forcing almost certainly significantly modifies net circulation patterns, and influences the transport routes of inflowing turbid water (Figure 20). If wind setup significantly deepens water in some areas at high tide, then contemporaneous waves will also be larger, and near bottom shear stresses will increase. It is probable that setups and wind driven surges are more common now than in the past, since the mean depth of the estuary has increased over at least the past 50 years. Maximum wave sizes will also have increased as a result of this deepening, and more stress will be transferred from wind to the water mass during storms. Thus supratidal flooding may be an increasingly common engineering problem in the low-lying areas adjacent to the estuary, some of which have only recently been built on.

Bathymetry

The AHE can be subdivided into a small number of distinctly different and internally consistent bathyforms (Figure 21). Eastern high tide slopes are usually low angle convex upwards features which demonstrate clear responses to wave energy (Figures 23 and 24). Intertidal channels and offshore mounds associated with the eastern high tide slopes in the south-eastern and central eastern parts of the estuary tend to align themselves normal to the dominant west wind and to migrate down-wind in a shorewards direction (Figure 26). Erosion and deposition of sediment on the eastern slopes tends to conserve their shapes, and contributes to the trend towards a wave-normal alignment of the bathymetry. Areas exposed to longest fetch waves exhibit quasi-stable forms in equilibrium with wave energy, reflecting the pervasive, macrobathymetric influence of waves in this estuary (Figure 30).

Deeper eastern flats are less well organised by waves, and their bathymetry is a compromise between wave and tidal current energy. Western slopes and flats also show an orderly response to wave energy, trending from relatively high angle concave upwards curvilinear profiles in the north, towards low angle concave upwards or nearly straight configurations in the south, as downfetch wave energy (wave frequency) increases. Although it is likely that sediment accumulations on these western slopes are a consequence of the large volumes of effluent released from CDB outfalls, there is no conclusive bathymetric evidence to prove or disprove the possibility (Figures 28 and 29).

Tidal currents, rather than wave energy, control the configurations of the central mounds, larger intertidal channels, and subtidal channels of this estuary.

A comparison of bathymetric data from surveys completed in 1920, 1962, and 1975/77 shows that the intertidal zone of the northern half of the AHE (and probably of the whole estuary) lost up to 1 m of sediment between 1920 and 1962, and that the intertidal flats continued to lose sediment between 1962 and 1975/77, but at slower rates. Since 1962 sediment has accumulated adjacent to the two river entrances, and off the oxidation pond outfalls, but most erosion and deposition was due to slight adjustments in subtidal channel alignments (see Maps 3 and 4, Appendix 1).

Surface sediment

The surface sediment analysed in this study was collected from an uppermost layer, which is actively responding to the present energy regime and is thus a sedimentation unit (Appendix 3). Samples were separated into sand and mud (at 0.0625 mm), and sand fraction size analyses were performed with a Woods Hole-type Rapid Sediment Analyser. A brief comparison of sieve and RSA analyses of representative surface sediment samples from the AHE indicates that there were major differences between the results obtained by each method, and it is probable that if sieve analyses had been used exclusively in this project the final conclusions would have been quite different (Figures 79 and 80).

1. *Mud.* The muddiest sediment in the AHE occurs at the mouths of the Avon and Heathcote Rivers, where areas of 240 000 m^2 and 600 000 m^2 respectively are muddier than 40%, and reach maximum values of almost 90% (Figure 33). Trends in sediment muddiness which approximately parallel bathymetric contours, and the absence of mud above the MTL in most areas exposed to relatively long fetch waves, indicate that wave energy exerts the principal control on mud deposition in this estuary. However, close to the two river mouths, mud deposition patterns appear

to be a compromise between the rate of supply, the distance from a source, and wave energy. The resulting patterns may be quite coherent, but it has not been possible to evaluate the relative importance of each process.

That the Heathcote depository is 2.5 times larger than the Avon, and 10% muddier, is interpreted to be the result of order of magnitude differences in the rates of supply of sediment, and an indication that the mean muddiness of these depositories is influenced significantly by preferential deposition close to an essentially point source.

The evidence of widespread erosion - when a brief literature survey suggests that estuaries are often almost perfect retainers of sediment - and the presence of coherent patterns of mud deposition in areas undergoing active erosion, are both apparently paradoxical observations. The discovery of a sensible explanation of these features is a major result of the analysis of subsurface sediment in Part Five.

Since much of the mud supplied to the AHE is deposited in areas undergoing net erosion, it is probable that this mud is only in residence for a short time. As a result it is predicted that pollutants adsorbed on to mud particles will tend to have short residence times, and bottom sediment will not be enriched in mud-borne pollutants.

Finally, there is no physical, depositional evidence that the release of effluent into the estuary from CDB oxidation ponds affects the deposition of mud in any way.

2. *Sand.* A review of the literature on methods of identifying environment-specific sediment textures leads up to the conclusion that bivariate grain size plots are of no value to this study, and that there is little to be gained from this approach. Methods which follow from the work of Moss (1962, 1963) and Visher (1969) are potentially useful analytical tools, and they provide plausible explanations of sand fraction size distributions of surface samples from the AHE.

A cluster analysis was used to sort all surface samples (about 480) into like groups. Six groups were identified, and these were interpreted to be arbitrary subdivisions of a continuous spectrum of grain-size distributions, and not six discrete and natural clusters (Figures 40 and 41). Two basic grain-size distributions were recognised; the first was characterised by sharply curvilinear or bilinear cumulative curves, interpreted to represent two log-normal subpopulations, one deposited from saltation and one from suspension

(Figures 37 and 38). The second basic distribution was characterised by straight or slightly curvilinear (rarely bilinear) curves, interpreted to represent a single log-normal population deposited from saltation. Within the first basic group (cluster Groups A to C) the two subpopulations appear to have largely independent properties - the saltation population is uniformly well sorted, whereas both the sorting and mean size of the suspension population varies from Group A to C. Within the second group (Groups D to F) sorting values are consistently excellent, but mean sizes increase from D to F.

Histograms of sample height above datum vs sample frequency for each of the cluster Groups A to E (Figure 42) show that in the series A-B-C samples occur preferentially below the MTL, and only 0.5% from above the HWONT line (about 9.5 m HAD). There were no differences in the depth preferences of the three Groups A, B and C. Groups D and E occur preferentially in shallow water, but the HAD histograms of these two groups are bimodal, indicating that a significant percentage of these samples occur on the deepest intertidal flats - adjacent to the throughgoing subtidal channels. These results mean that sediment is only commonly deposited from suspension below the MTL, in water deeper than about 1.2 m below HWOST. Analyses presented in Part Two indicate that below the MTL, near bottom shear stresses decrease rapidly with increasing depth. The threshold for the deposition of suspended sediment (and mud) is probably about 2 dynes/cm^2 - below this value, sediment is deposited from suspension; above it, sediment is not.

A map showing the cluster group identity of all surface samples from the AHE (Map 2) indicates that the distribution of sediment deposited from suspension in this estuary is a compromise between processes which supply sediment, and those which influence its deposition and transportation within the estuary. The sequence C-B-A, which occurs with increasing distance from the river entrance in the Heathcote Basin, is interpreted to be a preferential depositional feature. In areas above the MTL (away from the river entrances), the properties of surface sediment are governed by both water depth and fetch distances, so that with increasing effective fetch distances, and thus increasing shear stress frequencies, sediment of Group E occurs in progressively deeper water. The granulometric properties of Group E sediment remain constant downfetch, indicating that sediment granulometrics are independent of shear stress frequency, but dependent on absolute levels of shear stress.

Cumulative curve shapes are not process-specific in this estuary, and the available evidence indicates that they are probably shear stress-specific. This result has significant repercussions for the Visher approach to cumulative curve analysis, since it indicates that a fundamental assumption of this approach - that breaks or inflections in log-probability grain size distributions are environmentally diagnostic (Visher, 1969, 1977) - may be invalid. The results of this study indicate that shear stress levels, and the properties of material supplied to a particular environment, are the main determinants of log-probability curve shapes - the processes which exert the stress are not recoverable from the resulting size distributions.

The presence of large areas of active sediment with remarkably uniform properties indicates that much of the active sediment in this estuary is in equilibrium with the physical environment, and that relict material supplied by the continuing net erosion demonstrated in Part One is not a significant modifier of surface sediment properties. A comparison of the cluster group map and maps of net erosion and deposition (Maps 2, 3 and 4) indicates that this is a valid conclusion, since the two patterns are clearly independent.

An analysis of the granulometrics of individual bathyforms indicates that where longshore energy gradients occur (as along the western slopes), longshore sediment gradients also occur. However, shore-normal trends are usually dominant, in response to the dominant shore-normal trends in water depth, wave energy and tidal current energy. Where energy is uniformly distributed longshore (as along the eastern slopes and flats), and where the bathymetry is characterised by large areas with consistent heights above datum (as on the eastern 9.0 m and 9.5 m bathyforms), sediment properties are also uniform, and exhibit an approximately shore-parallel, constant depth zonation.

Subsurface sediment

Detailed logging of 47 cores of subsurface sediment from the AHE revealed the presence of a stratigraphy consisting of pre-estuarine sand, overlain by a layered estuarine sequence, which in turn is overlain by post-European (anthropogenic) mud. The uppermost 25 cm - 30 cm of most cores consists of intensely bioturbate mottled sediment (which may be considered as a fourth stratigraphic unit) overlain by a thin, active layer.

1. *Stratigraphy.* Pre-estuarine sand - unit (a) - is uniformly low in mud and uniformly very well sorted, although mean grain size values vary from about 1.9 to 3.2 psi. Unit (a) sediment is interpreted to have been deposited only from saltation. It belongs to the Christchurch Formation (of Suggate, 1958), and represents the top of a 50 m thick, massive sequence of shallow marine sediment deposited during post-glacial transgression of the Canterbury coastline. Contours drawn on top of this unit indicate that the two major throughgoing subtidal channels have probably occupied their present positions since the estuary was first enclosed from the sea (Figure 56). Any idea when?

The estuarine sequence - unit (b) - consists of plane-laminated sand, muddy sand and sandy mud (rarely mud), and exhibits both fining upwards and coarsening upwards sedimentation sequences. A cluster analysis of all unit (b) sand samples (with the same program previously used to cluster surface sediment samples) produced four cluster groups (Figure 57). Representative cumulative curves and summary bivariate plots (Figures 58 and 59) indicate that as with surface sediment, unit (b) sand fractions are separated by the clustering operation into groups of convenience, and that there is a continuous spectrum of log-normal distributions, between end members characterised by straight curves, and by sharply curvilinear or bilinear curves. A fifth sample group (b') consists of a laterally equivalent, shallow water version of b1 to b4.

Massive olive grey plastic (buttery) mud of unit (c) overlies unit (b) sediment in many cores, and was probably deposited as a blanket throughout the estuary. Mud of this unit is interpreted to be post-European in origin, and to represent material supplied to the estuary during the early urbanisation phase of the growth of Christchurch City. Thus the lower contact of this unit may be dated at about 1850 (when settlement by European migrants first began), and the upper contact (where preserved) at about 1900. A mean accumulation of 50 cm of unit (c) sediment throughout the estuary would have been sufficient to cause the 30% decrease in the tidal compartment that probably occurred over the period 1850-1900.

2. *Near-surface bioturbate sediment.* A variety of infaunal and epifaunal animals in the AHE modify surface and near-surface sediment. In particular the mudflat snail *Amphibola crenata* browses across the sediment surface, converting the most recently deposited

material into readily transported fecal aggregates, and effectively speeding the removal of fine sediment from the estuary. The bivalve *Macomona liliana* alters the physical properties of surface and subsurface sediment by burrowing to depths of about 25 cm, then ingesting surface sediment and egesting it to form mounds on the surface. Burrowing crabs excavate sediment from depths of up to 15 cm below the sediment surface, dumping it as mounds adjacent to their burrows. Polychaete worms may be present in high densities, and clearly alter the surface roughness and compactness of the bottom of the estuary, exerting an influence which although virtually unevaluated, must be of major significance. Burrows, tubes, and excavation and defecation mounds and hollows of the sort illustrated in Figures 65 and 66 create a biogenic microbathymetry (Heezen and Hollister, 1971; Myers, 1977) which may significantly alter near bottom shear stress values, and assist in the removal of recently deposited (and biodeposited, or reworked), friable sediment.

The bioturbate zone which results from the net effects of all this biological activity is probably turned over to a depth of 10-25 cm on a time scale of tens of days to tens of months. A thin skin of active sediment covers the upper surface of this bioturbate zone, and sediment below this active layer is muddier than the active layer in shallow water (above the MTL), but less muddy than the active layer in deeper water. While active layer muddiness is related to HAD, the muddiness of the upper 5 cm of bioturbate sediment is not. There are no systematic relationships between active layer sand properties and sand properties of samples from the bioturbate zone beneath, although the summary granulometrics of both sample types are broadly dependent on HAD. These results indicate that if the present project had been based on a different sampling method - perhaps 5 cm deep cores, or samples of more casual dimensions, the information detailed in Part Four would not have been obtained.

Recognition of the role of burrowing animals in the long- and short-term dynamics of this estuary has provided answers to several apparently paradoxical observations. Animals which excavate or defecate subsurface material on to the sediment surface assist in net erosion, and the removal of fine suspendible sediment, and generate patterns of net erosion and deposition which are unrelated to variations in wave or tide energy, and which are independent of present day rates of sediment supply. Thus there may be coherent sediment muddiness patterns, due to the deposition of mud on the sediment surface, in areas which are experiencing a net removal of sediment.

3. *Predictions*. It is probable that a net loss of sediment is occurring in this estuary because fine sediment is being exported seawards at a greater rate than it is being renewed. Thus, as long as muddy sediment is available to be mined by burrowers, a net loss will continue, the tidal compartment will continue to increase, erosion of the edges of the estuary will continue, and shore protection costs may rise, particularly where the estuary margins consist of erodible salt marsh or swamp deposits, or dune sand. Eventually a layer of uniformly clean sand will blanket much of the estuary - as is now the case in several areas, for example see cores 23, 25, 37 and 39. This layer of clean sand will act as a buffer between the ancient muddy sediment that remains, and the modern environment.

When the reservoir of biologically available virgin mud is worked out to a uniform depth - when all unit (b) and (c) sediment is buffered by a clean sandy surface layer - mud from external sources, probably reflecting a more polluted industrial source, may begin to predominate in the flux of fine sediment through the AHE. There is likely to be a steep increase in the near future, perhaps in the next 10-15 years. All remaining ancient, pre-industrial mud may be buffered by a sand layer within 25 years. The biological implications of this change in fine sediment sources may be far-reaching. Filter feeders and surface detritus-feeding animals which extract much of their food from finer particles, may decline in numbers as the reservoir of mud is mined out, and as suspended sediment concentrations decrease. Parallel adjustments to the remainder of the benthic community may result in significant long-term changes in the biological character of the Avon-Heathcote Estuary.