SEDIMENT TRANSPORT IN THE NEARSHORE MARINE ENVIRONMENT, TIMARU, NEW ZEALAND

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ABSTRACT

This study is concerned principally with obtaining direct measurements of nearshore sediment transport at Timaru using artificial tracers, with finding relationships between the measured transport rates and wave or wave-dependent parameters, and with investigating the practical application of the artificial tracing technique in nearshore sediment transport studies. All field work for the study was undertaken within an area extending approximately 5 km north and 3.6 km south of Timaru Harbour to a distance of 5 km offshore. Water depths in this area do not generally exceed 15 m.

The nearshore environment was investigated by examining the bathymetry, surface sediments, hydraulic conditions and depth of disturbance of sediment in the study area. It was found that there was considerable potential for wave-induced sediment transport at the 7 m isobath. Sediment transport is expected to increase shoreward and decrease seaward of this line.

Four sediment tracing experiments were undertaken. Experiment 1 used fluorescent tracer to obtain transport rates for sediments ranging in size from very fine sand to pebbles. A magnetic tracer, ironsand, was also used but was not successful. Experiment 2 used fluorescent tracer to determine transport rates for very fine sand. Results from these two experiments were used to look for relationships between transport rates and wave and wave-dependent parameters.

The relationships that were found were used to calculate long-term sediment transport rates, for three water depths, from one full year of recorded wave data. Ignoring the medium and coarse sand size classes (where representative long-term rates were not available) the calculated long-term transport rates ranged from 0.014 m^3 m^{-1} day^{-1} (granules) to 0.028 m^3 m^{-1} day^{-1} (very fine and very coarse sand) for the 7.6 m water depth, 0.009 m^3 m^{-1} day^{-1} (granules) to 0.016 m^3 m^{-1} day^{-1} (very coarse sand) for the 10.0 m water depth and 0.005 m^3 m^{-1} day^{-1} (fine sand) to 0.008 m^3 m^{-1} day^{-1} (very fine and very coarse sand) for the 12.2 m water depth. The calculated rate for very fine sand in the 7.6 m water depth was considerably lower than had previously been calculated for the area.

Experiment 3 used fluorescent tracer to assess whether coarse sediments could move from the nearshore seabed to the foreshore of a mixed sand and gravel beach. The results showed that waves with an average significant height slightly greater than 1.0 m, and an average wave period ranging from 9 - 11 s, are capable of moving pebbles up to 28.4 mm median diameter from the seafloor onto the beach. The beaches can therefore receive nourishment from the seafloor.

Investigations were undertaken to find an alternative to fluorescent tracer for tracing fine nearshore sands in New Zealand. A chemical tracer, europium labelled sand, was tested in the laboratory using atomic emission for detection. It was then used in a field test, experiment 4, but was found to lack sufficient sensitivity. Sensitivity would have to be improved if this tracer type is to be used successfully for future experiments.

Results from experiments 1 and 2 showed that there was a wave-induced net landward movement of all grain sizes tested, with an increasing tendency for landward movement with increasing grain size. It is proposed that coarse sediments will eventually end up on the beaches but that the onshore movement of finer sediments is balanced by an increasing offshore gravitational component as the coast is approached. This pattern of predominant on-offshore movement is contrary to the pattern of dominant longshore movement suggested for the area by other workers. It is also proposed that the processes operating on the beaches, in the nearshore, and on the shelf proper are quite different and therefore it is not satisfactory to represent movement over the entire area by a single transport rate.

It is thought that a slightly modified version of the null point theory best explains the observed patterns of movement in the study area. In the study area the gradient of the seafloor decreases in a seaward direction so that a particle seaward of its neutral line will move shoreward and a particle shoreward of its neutral line will move seaward.

Sedimentation in Timaru Harbour entrance channel and the dispersion of dredge spoil are considered briefly in the light of the results from this study.

A number of suggestions are made concerning the practical application of the artificial tracing technique in nearshore sediment transport studies. The assumptions required for the spatial integration method can be satisfied in the nearshore. However, there is some uncertainty regarding the importance of tracer accounting procedures.

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

This thesis deals with sediment transport in the nearshore, shallow marine environment at Timaru, New Zealand. The coastline in the Timaru area is dominated by mixed sand and gravel beaches which extend only a short distance offshore where an abrupt change in gradient and sediment texture marks the beginning of the continental shelf. The inner continental shelf is mantled with a layer of very fine sand with an occasional patch of gravel. The area is exposed to high energy waves which cause considerable sediment transport on both the beaches and the inner continental shelf. This transport of sediments has important physical and economic implications in the Timaru area.

On a world scale very little is known about nearshore sediment transport and reliable measurements of transport rates are scarce. Consequently, this study had the following major objectives:

a) To obtain direct measurements of both the rates and directions of nearshore sediment transport at Timaru using artificial tracers.

b) To find relationships between the measured sediment transport rates and wave or wave-dependent parameters so that long-term sediment transport rates could be determined from wave records.

c) To investigate the practical application of artificial tracing techniques in the study of nearshore sediment transport.

The nature of our understanding of nearshore sediment transportation is such that any study of this kind inevitably raises fundamental questions concerning the adequacy of both the theories of wave-induced nearshore sediment transport and the available measurement techniques. For these reasons it is appropriate to introduce this investigation with a review of these matters.

1.2 NATURE OF THE CONTINENTAL SHELF

The "continental shelf" is defined as the zone bordering a continent and extending from the low water line to the depth (usually about 180 m) where there is a marked or rather steep descent toward a greater depth (U.S. Coastal Engineering Research Center 1977, p. A-7). Globally, the edge of the continental shelf ranges in depth from 20 to 550 m, with an average of 133 m, and the width ranges from zero to 1500 km, with an average of 78 km (Emery 1969). Johnson (1919) proposed that the continental shelf develops as the coast retreats and that it consists of an inner wave cut platform and an outer wave built depositional terrace.

A profile of equilibrium was thought to be reached when the processes of erosion, weathering and transportation are balanced. This profile should be steepest near the land, where sediment is coarsest and most abundant, and progressively less steep in a seaward direction where the sediments have become finer through abrasion. Over the entire shelf the slope is theoretically of the exact steepness required to enable the wave energy at any point to dispose of the volume and size of sediment being transported. Related to this hypothesis is the concept of the size-graded shelf. This states that sediment size will decrease across the shelf in a seaward direction as an indirect function of depth and a direct function of the amount of wave energy penetrating to the bottom (Swift 1970). Subsequent studies of shelf sediment distribution, however, did not find a seaward decrease in grain size (see for example Shepard 1932, 1939; Emery 1952). Rather a variety of sediment types were found to comprise a complex distribution. Based on their ages, the main sediment types have come to be classified as "relict", "modern", or "palimpsest".

Relict sediments are defined as sediments remnant from an earlier environment (Emery 1952). They are not in equilibrium with the present environment. Modern sediments are defined as sediments that are presently being supplied to the shelf (Curray 1965). They are in equilibrium with the present environmental conditions.

Palimpsest sediments are defined as sediments which exhibit attributes of an earlier depositional environment and also attributes of a later environment due to reworking

(Swift, Stanley and Curray 1971).

Modern sediments can be differentiated into two separate facies based on their mechanism of transport (Swift 1970). Bedload is hydraulically concentrated in the "near-shore modern sand prism" which consists of a mainland beach, spit, or barrier island plus a seaward thinning and fining wedge of nearshore sand. Suspended load is deposited further offshore in the "shelf modern mud blanket" (Swift 1970).

The submarine surface of the nearshore modern sand prism can be referred to as the "inner continental shelf". On unconsolidated coasts the inner shelf can be divided in turn into two morphologic elements, the "shoreface" and the "inner shelf floor" (Swift 1976). The shoreface extends from the shore down to depths of 12 to 20 m where the inner shelf floor lies. The upper section of the shoreface is defined here as the "nearshore". Figure 1.1 shows the inner continental shelf zones diagramatically.

1.3 WAVE-INDUCED CURRENTS AND NEARSHORE SEDIMENT TRANSPORT.

Horizontal currents are produced beneath waves in response to the motion of individual water particles. In deep water (depth greater than half the wavelength) the individual particle motion is circular. At the surface the diameter of the orbital motion is equal to the wave height but it decreases exponentially with distance below the surface (Inman 1963). As the wave travels into progressively shallower water the bottom acts as a boundary to the wave

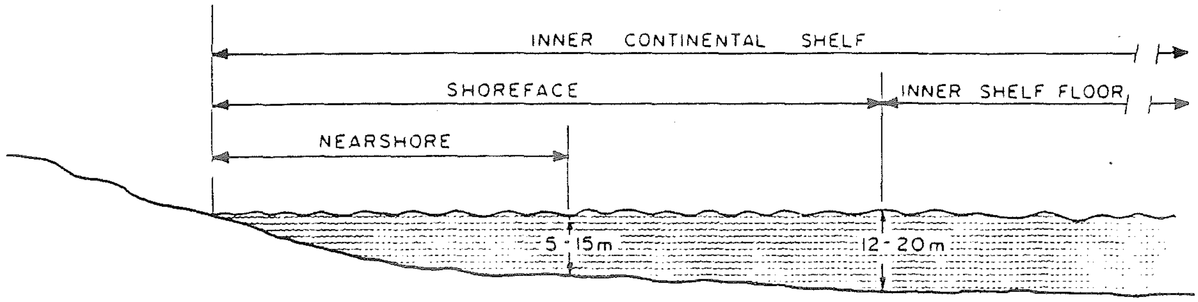


FIGURE 1.1 INNER CONTINENTAL SHELF ZONES.

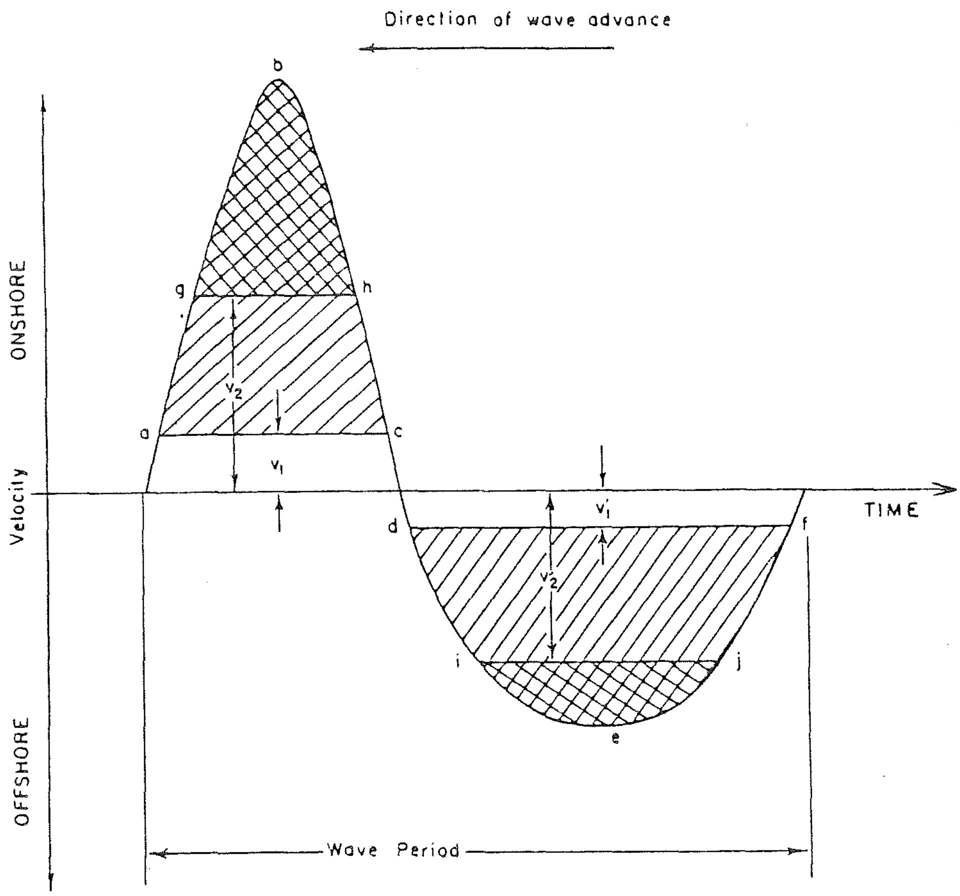


FIGURE 1.2 VELOCITY-TIME GRAPH FOR A WAVE-INDUCED HORIZONTAL OSCILLATORY CURRENT IN THE NEARSHORE ILLUSTRATING THE NULL POINT THEORY. FROM ZENKOVICH (1967, P. 102).

motion and the wave is transformed. The principal effect of the bottom is to reduce the vertical movements of water particles and therefore, in order to conserve energy, the orbits of the water particles must be flattened from circles to ellipses (Mason 1951). In relatively shallow water the vertical movement at the bottom ceases and the orbital motion there is simply a back and forth motion. These effects have been verified in wave tank experiments (Mason 1951; Wiegel 1964).

The shape of the wave profile is also changed as the wave travels into progressively shallower water. The crest becomes shorter and steeper and the trough longer and flatter (Zenkovich 1967, p. 29). The oscillatory currents beneath the wave change in proportion to the profile change, so that at the bottom there is a high magnitude current of short duration in a landward direction under the crest and a lower magnitude current of longer duration in a seaward direction under the trough. This effect was observed in the field by Inman and Nasu (1956). Cook (1969) and Cook and Gorsline (1972), however, found asymmetries in wave-induced currents to be variable, although for long period waves landward currents predominated.

In shallow water the orbital motion of water particles is not closed (U.S. Coastal Engineering Research Center 1977, p. 4-41) which results in a mass transport of water in the direction of wave advance. In order to satisfy continuity the mass transport of water in the direction of wave advance must be balanced by a return flow. Longuet-Higgins (1953) found that theoretically the mass transport was in the direction of wave advance near the surface and at the bottom and that this was balanced by a net flow in the opposite direction at mid-depths. This pattern has been observed in wave tank experiments (see for example King 1972, p. 106).

One way in which the asymmetry in the wave-induced horizontal oscillatory currents could influence sediment transport was outlined by Cornish (1898). He noted that the high velocity current under the crest could be sufficient to move coarse particles in a shoreward direction but that the low velocity current under the trough could be insufficient to move the particles in a seaward direction. This would result in a net movement of coarse material shoreward. Finer sediment could be moved in both directions, but, if there was either a general seaward drift of water or the bottom sloped seaward, the finer particles would move a net distance seaward. It would therefore be possible to have simultaneous movement of coarse and fine sediment in opposite directions.

Cornaglia in Zenkovich (1967, p. 101) proposed an extended theory relating nearshore sediment movement on a sloping bottom to the asymmetry of wave-induced horizontal oscillatory currents. The theory is mentioned briefly in a translation of Cornaglia (1889) in Fisher and Dolan (1977, pp 11-26) but the description here is based on Zenkovich (1967, p. 101). The theory assumes that the threshold velocity required to move sediment onshore is greater than that required to move it offshore because the gravitational force will oppose onshore (upslope) movement and assist offshore (downslope) movement.

Consider the velocity-time graph presented in figure 1.2 for wave-induced horizontal currents beneath a shoaling wave. A small particle, with an onshore threshold V_1 and an offshore threshold V_1', will move onshore under the crest a distance proportional to the area 'abc' and offshore under the trough a distance proportional to the area 'def'. Because the area 'def' is greater than the area 'abc' the particle will move a net distance offshore. A larger particle, with an onshore threshold V_2 and an offshore threshold V_2', will move onshore under the crest a distance proportional to the area 'gbh' and offshore under the trough a distance proportional to the area 'iej'. In this case the area 'gbh' is greater than the area 'iej' and the particle will move a net distance onshore. If a range of particle sizes is present then for one size the areas cut off from the upper and lower portions will be equal and the particle will oscillate under the crest and trough but the net movement will be zero.

For a given particle size, bottom slope and wave condition there will be one point at which the net particle movement is zero. This point is called the null point, which, in two dimensions, will form a neutral line parallel to the direction of wave advance. At depths greater than its neutral line a particle will move offshore because the degree of wave asymmetry is less and conversely at depths smaller than the neutral line a particle will move onshore because of the increased asymmetry.

For a given bottom slope and wave condition there should be a neutral line for each size of sediment. The position of the neutral line is controlled by three factors (Zenkovich 1967, p. 103):

a) The steeper the bottom slope the greater the difference in the onshore threshold velocities which means that the current asymmetry must be greater to overcome this effect. Therefore for a steeper slope the neutral line will be further onshore for all sediment sizes.

b) The larger the waves the further offshore current asymmetry occurs and therefore the neutral line for all sediment sizes will be further offshore.

c) The larger the particle the larger the magnitude of the threshold velocities and therefore "the less may the forward velocity of the water exceed the backward velocity on its neutral line for a given size of wave. This means that the larger a particle is, the farther will its neutral line be from the shore."

Zenkovich (1967, p. 103) states later:

> If there are particles of various sizes at any point on the bottom, a wave disturbance of a given strength will move small particles down the slope and will simultaneously move large particles up the slope; and particles of a certain size will remain in position, since their neutral line passes through the point.

The statement that the larger a particle is the farther offshore its neutral line will be, other factors equal, and the above statement on sediment sorting are at variance with other interpretations of the theory. Munch-Petersen (1950), Swift (1970) and Komar (1976, p. 311), for example, state that the larger a particle is the closer will its neutral line be to the shore. Therefore, according to Komar (1976, p. 311):

> If many different sizes are present at a certain location, only one of the grain sizes can be at its null point: the larger grains will move offshore according to the hypothesis, and finer ones will move shoreward.

This latter interpretation is believed to be the correct one for the original theory because Cornaglia (1889) translated in Fisher and Dolan (1977, p. 22) states: "...the neutral line deepens...as the specific weight and volume of the sediment decrease".

The null point theory has dominated papers on wave-driven nearshore sediment transport (Swift 1970). The theory has been evaluated theoretically, in the laboratory, and in the field with mixed results. Munch-Petersen (1950) believed the theory was invalid because the influence of gravity is minimal compared with the wave-induced currents. Ippen and Eagleson (1955) undertook a laboratory experiment and found results in agreement with the null point theory. They developed an empirical model relating local wave conditions to water depth and grain size. Miller and Zeigler (1958, 1964) compared observed grain-size curves on two Massachusetts beaches with those predicted by the empirical model of Ippen and Eagleson (1955). For one beach good agreement with the model was found while for the other beach only partial agreement was obtained. Harrison and Alamo (1964) compared trends of mean size and sorting with those predicted by a null point model of Miller and Zeigler (1958) and found poor agreement. Vernon (1966) used the null point model to explain observed sediment movement during a study on the continental shelf off California. Zenkovich (1967, p. 104) noted that the model fails to take mass transport into account or the possibility of sediment being placed in suspension. Zenkovich (1967, p. 120) also noted that sand bottom slopes rarely exceed 1° and therefore the gravitational component is minimal. Zenkovich (1946d) in Zenkovich (1967, p. 103) released a mixture of dyed particles containing a wide range of sediment sizes. The coarser particles moved onshore, the finer particles offshore, while those with the same grain size as the native sediment remained in oscillating equilibrium. This pattern of movement supports Zenkovich's interpretation of the null point theory but, although it demonstrates the existence of a null point, it contradicts the generally accepted theory. Cook (1969) and Cook and Gorsline (1972) in a field study on the continental shelf off California found asymmetries in wave-induced currents to be variable, with both onshore and offshore currents dominating. Long period waves caused onshore currents to predominate. Coarse sediment was found to move in the direction of wave advance while fine sediment moved in response to inequalities in the velocity of onshore and offshore currents. Gravity was not thought to affect the movement of fine sand across ripples. Swift (1970) noted that the theory fails to take into account other mechanisms that may be operating such as rip currents or suspended sediment transport. Graf (1976) used the empirical model of Ippen and Eagleson (1955) and a theoretical null point model developed by Eagleson and Dean (1961) to predict nearshore sediment textural patterns on part of south-western Lake Michigan. The predicted sediment sizes were too large, although many aspects of the pattern were predicted correctly. Jago and Barusseau (1981) used the model of Eagleson and Dean (1961) to predict sediment textural patterns on the Roussillon coast of France. They found that the trend of textural gradient was predicted but not its magnitude.

There is therefore not only some confusion over the interpretation of the null point theory but also conflicting evidence regarding its validity.

Grant (1943) proposed an alternative theory for nearshore sediment transport. The theory assumes that all bedload sediment transport will be in the direction of wave advance because of the asymmetry in the wave-induced currents and because of the mass transport effect. Offshore movement would occur principally through rip currents. Sato, Ijima and Tanaka (1963), in a field experiment off the coast of Japan, found that sand was transported in the direction of wave advance provided that tidal currents were minimal. Cook and Gorsline (1972), however, found that the direction of the predominant wave-induced current was variable and they therefore discounted Grant's theory.

Niedoroda and Swift (1981) measured and calculated wave-induced currents in the nearshore. They found that in water depths less than 10 m the wave-induced oscillatory currents were sufficiently asymmetric to cause a net onshore transport of sediment. They believed that if equilibrium was to be approached or maintained in this area the tendency for onshore drift must be balanced by an offshore gravitational component. The balance between on-offshore bedload transport would be controlled by slowly varying currents caused by wind-driven upwelling or downwelling.

The theories of Cornish (1898), Cornaglia *in* Zenkovich (1967, p. 101) and Niedoroda and Swift (1981) all indicate that the relationships between wave-induced oscillatory currents and nearshore sediment transport are complex but sensitive. A small change in one parameter may, for example, change the net movement from onshore to offshore. This makes it difficult to predict sediment transport rates because of the variability of ocean waves.

In this discussion of nearshore sediment transport by wave-induced currents mention has been made of on-offshore transport. If, however, waves are travelling at some angle to the coastline there will be a component of longshore transport in addition to the on-offshore transport. This longshore transport is distinct from the transport resulting from longshore currents in the surf zone. Such littoral currents are restricted mainly to the zone between the breakers and the shore (U.S. Coastal Engineering Research Center 1977, p. 4-45). The present study is primarily concerned with bedload transport seaward of the surf zone and therefore the longshore transport of sand by breaking wave-induced longshore currents is not considered further here.

It must also be remembered that although wave-induced currents dominate the nearshore there are other currents, such as tidal currents, present as well. These currents will become relatively more important for sediment transport as water depth increases because both the magnitude and asymmetry of wave-induced currents decrease with increasing water depth.

1.4 TECHNIQUES USED IN THE STUDY OF MARINE SEDIMENT TRANSPORT

This section will outline some of the techniques that have been employed to study marine sediment transport. The sediment tracer technique is outlined in greater detail than the other techniques because it is a major focus of the present study. Examples of studies that are given have been restricted to the nearshore as much as possible but also include some examples from other areas of the marine environment where the technique would be applicable in the nearshore. Although examples have been classified into separate categories a number of the studies cited used a combination of techniques to measure or infer sediment transport. Many of these techniques give only the direction and not the rate of sediment transport.

1.4.1 Hydrodynamic

In this approach hydraulic conditions (mainly waves and near bottom currents) are either measured and/or calculated from theory and sediment transport is then either:

a) Calculated from theoretical or laboratory derived formulae; or

b) Inferred by comparing measured and/or calculated currents with threshold values for sediment movement; or

c) Inferred from bottom photographs taken during the measurement of hydraulic conditions, or

d) Inferred from some combination of the above. This approach dominates recent literature on marine sediment transport with recent studies by Kachel and Sternberg (1971), Bigham (1973), Carter (1977), Gadd, Lavelle and Swift (1978), Cacchione and Drake (1979), Davies and Wilkinson (1979), Drake, Totman and Wiberg (1979), Harris *et al.* (1979), Figueiredo (1980), Freeland *et al.* (1981), Vincent, Swift and Hillard (1981) and Vincent, Young and Swift (1982).

1.4.2 Sediment Traps

When using this method to study sediment transport a device is placed on the seabed to trap moving sediment. Given the size of the trap entrance an estimate of the sediment transport rate can be obtained by measuring the amount of sediment trapped during a specified time interval. This technique has been used by Bruun (1969), Cook (1969), Cook and Gorsline (1972) and by Gillie (1979).

1.4.3 Bedforms

The direction of net sediment transport can be inferred from the orientation and shape of large scale bedforms on the seafloor. Examples of studies using this method are Belderson and Kenyon (1969) and Caston (1981). Stride and Cartwright (1958) estimated the rate of advance of sand waves in the North Sea and used this to estimate the net sand transport rate across a 64 km plane.

1.4.4 Bathymetry

Sediment transport can be inferred from changes in the bathymetry of an area. This technique has been used to estimate transport over both the short term (days or months) (Gillie 1979) and the long term (years) (De Alteris et al. 1975; Carter 1977). This technique is usually used in combination with some other technique.

1.4.5 Wrecks

Scour and deposition of sediment around wrecks has been used as an indicator of net sediment transport direction. Examples are studies by De Alteris et al. (1975) and Caston (1979).

1.4.6 Practical Experience

Sedimentation rates in dredged channels or pits can be used to calculate sediment transport rates. These rates will be minimum estimates only because not all moving sediment is necessarily trapped. Examples of studies employing this technique are Vinjé (1968) and Tierney (1977).

1.4.7 Tracers

Sauzay (1973, p. 4) has defined the term "tracer" when used in sedimentology as, "any property or characteristic that makes it possible to follow the dynamic behaviour of a sediment". Tracers are "artificial" if they are deliberately added by man or "natural" if they are not intentionally added by man for the purposes of a dynamic study (Sauzay 1973).

1.4.7.1 Natural Tracers

A variety of natural tracers have been used to study sediment transport in the marine environment. Several examples are given below.

Kamel (1962) studied naturally radioactive thorium in heavy minerals along a section of the Californian coast. A decrease in the concentrations of both thorium and heavy minerals from a source area was used to infer the direction of sediment transport.

Mineral composition has been used to indicate sediment transport paths by a number of workers (see for example Trask 1952; McMaster 1960; Byrne and Kulm 1967; Judge 1970; Healy 1982). Provided a source area for a particular mineral can be identified the direction of sediment transport can be inferred from the relative concentration of this mineral in samples collected in areas away from the source.

Coulbourn and Resig (1975) used foraminifera as natural tracers in a Hawaiian bay. Of the 53 species of foraminifera found in sediment samples from the bay, 16 species had distribution patterns that provided evidence on sediment transport directions. These patterns were in agreement with data obtained from physical measurements in the bay.

Lingwood (1976) studied the progressive breakdown of shells with distance from a living population and used this to infer sediment transport directions in Liverpool Bay. The findings of this study indicated an offshore movement of sediment although most workers in the area had suggested that movement was onshore. This difference may be a result of the shell material having a different specific gravity to the sediment which would make it hydraulically inequivalent to the sediment and therefore not a good indicator of sediment transport.

Booth (1973) used textural changes as an indicator of sediment dispersion in the Northern Channel Island Passages, California. The basis for this method were the assumptions that mean grain size will increase with increased energy and that sorting will be poorer with both increased energy and a greater range of energy conditions. Therefore if a set of samples is assumed to be in textural equilibrium with the environment then data on mean grain size and sorting from these samples should provide information on bottom current patterns and hence sediment dispersion patterns.

Grain shape is another sediment parameter that can be used as a natural sediment tracer. Winkelmolen (1969, 1971) measured the rollability of sand grains in a specially designed rollability apparatus to provide a measure of sand grain shape. By computing relative rollability values for a number of samples, sources and sinks of sediment could be identified. An example of the application of this technique is presented in section 2.3. Ehrlich, Orzeck and Weinberg (1974) used the maximum projection shape of sand grains to identify sources and the proportionate contribution of each source to a section of beach on the Californian coast.

Natural tracers are limited at best to providing information on sediment transport patterns, usually on a long term basis. They do not provide any information on rates of sediment transport or on the specific mechanisms by which grains of differing characteristics have been eroded, entrained or emplaced.

1.4.7.2 Artificial Tracers

The principle of the artificial tracer technique is that a tracer, which must have some characteristic that distinguishes it from the natural sediment in the study area, is released into the environment being studied and its subsequent movement is followed to provide a measure of sediment transport in that area. The advantage that artificial tracers has over natural tracers is that by controlling the source of sediment (that is, the tracer released) transport rates as well as directions can be determined. Other advantages that the artificial tracer technique have over other techniques used to study marine sediment transport are that the movement is measured directly (Knoth and Nummedal 1977) and that an understanding of the physics of water motion and sediment-water interaction is not required (Duane and James 1980).

Inman and Chamberlain (1959) and Crickmore (1976) have defined five criteria that should be satisfied by an artificial tracer. The tracer should:

a) Behave hydraulically in the same way as the natural sediment it is simulating. Therefore the tracer should have the same size, shape, specific gravity and surface properties as the natural sediment under study.

b) Be easily and rapidly distinguishable from the natural sediment and be capable of identification at low concentrations.

c) Be inexpensive and available in the amounts required to provide adequate concentrations for the duration of the experiment.

d) Not constitute a safety hazard to the public or to marine life.

e) Retain its identification property for the duration of the experiment.

A variety of artificial tracer types are used in the marine environment. The different types can be arbitrarily classified according to the distinguishing property or characteristic of the tracer that enables detection. The following types can be identified:

a) Foreign Tracers Particles that are not present naturally at a study site can be used as sediment tracers. Both artificial and natural particles have been used. Kidson and Carr (1961) used fireclay markers in a beach tracing experiment at Bridgewater Bay, Somerset, and

Matthews (1980a) used brick chips in a beach tracing experiment at Wellington Harbour, New Zealand. It is unlikely that either of these artificial tracers behaved hydraulically in the same way as the natural sediment they were simulating. Baker (1956) used natural sand of a foreign mineral type to trace sand movement at Portland, Victoria, Australia, and Carr (1971) used natural beach pebbles of foreign geological types to tracer pebble movement on Chesil Beach, England.

Before choosing a foreign natural tracer all the mineral types present in the study area must be identified and for sand sized sediment this may involve a considerable amount of work. For pebble sized sediment in situ detection is possible but for finer sediments samples must be collected for analysis. The analysis may be very time consuming.

b) Magnetic Tracers Particles with magnetic properties may be used as sediment tracers. Pantin (1961) used magnetic concrete as a sediment tracer in Cook Strait, New Zealand, and Matthews (1980b) used ironsand as a sediment tracer at Fitzroy Bay, Wellington, New Zealand. In both cases samples were collected for analysis. It is unlikely that either of these tracers behaved hydraulically in the same way as the natural sediment they were simulating. Wright, Cross and Webber (1978, 1979) used aluminium pebbles in a tracing experiment at Hengistbury Long Beach, Poole Bay, Dorset. The pebbles were manufactured with the same size, shape and specific gravity as the natural sediment under study and could be readily detected *in situ* by a metal detector even when buried below the surface. The main disadvantage of the aluminium pebbles was their high production cost.

c) Coloured Tracers Sediment can be dyed or painted and used as a sediment tracer. Chapman and Smith (1977) used coloured sand for a large scale tracing experiment on the Gold Coast, Queensland, Australia. Sampling was required and the coloured sand could only be distinguished under optical magnification. Caldwell (1983) used painted pebbles in a tracing experiment on Gileston Beach, U.K. *In situ* detection was possible because of the large particle size. This technique is well suited for pebble sized sediment but its use for sand sized sediment is limited because of the difficulty of detection.

d) Radioactive Tracers Natural or artificial sediment can be labelled with a radioactive material and used as a sediment tracer. Detection is achieved by measuring the radiation given off by the tracer and can be carried out *in situ* with even buried tracer being detected. This is the main advantage of this technique which has been used by a large number of workers. Labelling is usually achieved by one of three methods:

i) The radioactive material is incorporated onto the surface of natural sediment from the study site. Examples of studies using this technique are Kidson, Carr and Smith (1958), Kidson and Carr (1959), Courtois and Monaco (1969) and Lavelle *et al.* (1978).

ii) An artificial glass can be manufactured containing a suitable element that can be activated before release. The glass is manufactured to match the natural sediment as closely as possible. Examples of studies using this method are Sato, Ijima and Tanaka (1963) and Heathershaw and Carr (1977).

iii) For pebbles a hole can be drilled in each pebble and a small amount of radioactive material inserted and sealed in place with an epoxy resin. An example of a study using this technique is Steers and Smith (1956).

The advantages and disadvantages of radioactive tracers are discussed later in this section.

e) Fluorescent Tracers Natural or artificial sediment can be labelled with a selected substance which emits fluorescence upon excitation with ultraviolet light. With the exception of pebble sized sediment, which can be detected *in situ*, fluorescent tracing experiments require sampling to allow accurate detection. Labelling of natural sediment with fluorescent dye is discussed in section 4.3.2. Artificial particles incorporating fluorescent pigments have been used by Reid and Jolliffe (1961) and Jolliffe (1964) to trace the movement of beach pebbles. Fluorescent tracers have been used by a large number of workers and a good review of their use in the nearshore is given by Ingle and Gorsline (1973).

The term "luminophor" is interchangable with fluorescent tracer (Teleki 1966). The advantages and disadvantages of the fluorescent tracer technique are discussed later in this section.

f) Chemical Tracers Sediment can be labelled with an element that is subsequently detected by neutron activation analysis, X-ray fluorescence, atomic absorption analysis or atomic emission analysis. This category includes the tracers often referred to as "activatable tracers" which use neutron activation analysis for detection. The only field studies known to the author using this technique are Malone (1969) and Leahy *et al.* (1976) (see also Ecker, Sustar and Harvey 1977). The use of chemical tracers is discussed more fully in chapter 7.

Of all the categories of artificial tracers listed by far the majority of studies have used either radioactive or fluorescent tracers. The reason for this is simply that these types more easily satisfy the criteria outlined earlier for an artificial sediment tracer. The advantages and disadvantages of using radioactive and fluorescent tracers are listed below and have been compiled from Ingle (1966), Teleki (1966), Sauzay (1973) and Crickmore (1976).

a) Radioactive Tracers

Advantages

i) A variety of radioactive isotopes with characteristic energies and half-lifes are available for different types of studies.

ii) *In situ* detection possible, even if particle buried.

iii) Activity recorded is proportional to mass, except for shingle.

iv) Labelling technique suitable for silt, sand and shingle.

v) High detection sensitivity (7 particles per square metre).

Disadvantages

i) Safety hazards - to the operators
- to the population
- to the environment
- during transport

ii) Require a specialised laboratory with staff and equipment for field measurements.

iii) Relatively high cost.

iv) Unable to trace different size fractions simultaneously.

b) Fluorescent Tracers

Advantages

i) Preparation and handling are easy.

ii) A variety of colours can be used to differentiate between successive tests at one locality or to trace the movement of different size fractions.

iii) Sand, gravel and shingle can be labelled.

iv) Samples do not have to be analysed immediately following collection.

v) Relatively low cost.

vi) Available in large quantities.

vii) Sensitivity: 1 particle in 10^6 natural particles.

Disadvantages

i) Detection by sampling

ii) Immersion of large masses, which therefore causes disturbances to the local sediment and flow patterns.

iii) Not suitable for sediment finer than very fine sand.

iv) Time consuming because of sampling and counting procedures.

Studies using artificial tracers can be either qualitative or quantitative. With qualitative studies the general direction of transport is obtained and, if several surveys have been undertaken, the average grain velocity can be calculated. To obtain quantitative data one of three methods can be used. The "time integration method" involves measuring the change in tracer concentration downdrift from an injection point. The "steady dilution method" is similar to the time integration method but in this case the tracer is injected continuously. Both of these methods represent an Eulerian approach and are strictly applicable under conditions of steady unidirectional transport only (Crickmore 1967). They are therefore not suited to measuring sediment transport in the nearshore. The "spatial integration method" is basically a Lagrangian approach where sediment transport rates are obtained from successive surveys of the spatial distribution of the tracer (Crickmore 1976). The centroid of the tracer distribution for each survey is calculated. The positional shifts of the centroid between each survey are then used to calculate the average grain velocity. The relationship between average grain velocity and centroid movement was established by Crickmore and Lean (1962) in a flume study. If the thickness of the mobile layer is established this can be used with the average grain velocity to calculate the sediment transport rate. The thickness value is a critical parameter because it is directly proportional to the transport rate. Komar and Inman (1970) described it as the most uncertain of all parameters measured. Gaughan (1979) and Inman et al. (1981) have tested different measures of the thickness of the mobile layer. These measures are outlined in section 5.9.3.

The spatial integration method is applicable to both steady and non-steady unidirectional and two-way transport (Crickmore 1967, 1976). It must be assumed, however, that transport is more or less uniform in the study area (Crickmore 1976) and that tracer behaviour is independent of the manner in which it was introduced (Greer and Madsen 1979). In addition, all tracer particles initiall injected must be accounted for (Greer and Madsen 1979).

1.5 APPLIED ASPECTS

Many activities in the coastal zone require or would benefit from a knowledge of nearshore sediment transport patterns. Harbours and their associated entrance channels often require dredging to maintain the depths required for safe navigation. The amount of siltation that can be expected is useful in planning and costing dredging operations. If the dredge spoil is to be disposed of at sea a knowledge of sediment transport patterns is essential for an efficient operation. For example, if the spoil is dumped too close to or updrift from the harbour or channel it may return in a short period of time and require redredging. On the other hand, the material may be transported a greater distance than is necessary, thereby increasing the cost of the operation. Also, if spoil is dumped at a location where the sediment transporting power is insufficient to completely dispose of it a mound may form on the seafloor. This mound may alter wave refraction patterns in the area with detrimental effects on the local coastline. The mound may also prove to be a navigation hazard. A knowledge of nearshore sediment transport patterns assists in the selection of an appropriate disposal site.

Offshore mining of sand and gravel is another activity that requires a knowledge of nearshore sediment transport. Price, Motyka and Jaffrey (1979) reported that sea dredged aggregate accounted for 11% of the total sand and gravel production in the United Kingdom in 1976. As suitable land based resources are used up there will be increasing pressure to mine the seabed. If not well planned mining could have serious impacts on nearby coast-lines. For example, mining could deprive beaches of a sediment source by removing the source material or by trapping sediment moving onshore. Beach material may also be drawn down into a dredged hole and therefore be lost from the beach (Price, Motyka and Jaffrey 1979). If these impacts are to be avoided the mining operation must be situated far enough from shore to ensure that the sediment supply to the beach is not affected. Choosing the site therefore requires a knowledge of nearshore sediment transport patterns.

One further activity requiring a knowledge of nearshore sediment transport is beach renourishment. Renourishment can be achieved by the direct placement of sediment on the beach or by deposition of sediment in the nearshore. The latter technique relies on wave and current action to transport the sediment shoreward into the surf zone and hence renourish the beach. For this to happen the sediment must be placed at a site where shoreward transport occurs. Choosing this site therefore requires a knowledge of nearshore sediment transport patterns.

In some locations sediment for renourishment operations is obtained from the dredging of harbours or entrance channels (see for example Schwartz and Musialowski 1977, 1980). In other locations offshore borrow areas are used (see for example Walton and Purpura 1977; Jennings 1982). In the latter case the same impacts outlined above for offshore mining can occur if the borrow area is not correctly sited.

1.6 THESIS RATIONALE

Creager and Sternberg (1972) have noted that there has been a lack of field measurements of sediment transport on continental shelves. Swift (1972, p. 368) states:

> We are justly proud of our present concern with the hydraulic regime, but the outlines and dimensions of shelf sediment transport will continue to elude us until we undertake to directly monitor the sediment flux itself by sediment traps, tracers, time lapse photography, microbathymetric time series, or other means.

Despite this need for direct measurement it was noted earlier that recent studies of marine sediment transport have concentrated on measuring hydraulic conditions and then inferring sediment transport from the data.

The area seaward of the surf zone to a depth of 25 m is often neglected in studies of sediment transport and beach development (Aubrey, Twichell and Pfirman 1982). This area encompasses the nearshore, an area lacking in reliable data on the rates and directions of sediment transport (Ingle and Gorsline 1973).

It was the above reasons that a field study was undertaken with the aim of obtaining direct measurements of nearshore sediment transport. Such measurements would be of value to both the scientific community and to those involved in the planning and management of coastal areas. Artificial tracers were considered to provide the best means of obtaining the measurements and so were employed for this study.

Few studies have used artificial tracers to quantitatively measure sediment transport rates seaward of the surf zone. For this reason the present study became concerned with the practical application of artificial tracers in the study of nearshore sediment transport. This became a major focus of the thesis.

1.7 THESIS OUTLINE

The remainder of this thesis is divided into eight chapters. Chapter 2 describes the study area and reviews previous work on sediment transport in the area. A list is then presented summarising the current state of knowledge of the Timaru coastal environment. The chapter concludes by listing the specific aims of the present study. Chapter 3 describes aspects of the nearshore environment at Timaru that are considered important with respect to nearshore sediment transport. These include bathymetry, surface sediments, hydraulic conditions and the depth of disturbance of sediment. This information is then used to evaluate the potential for nearshore sediment transport. Chapter 4 details the methodology and findings of an experiment that used both fluorescent and magnetic tracer sediment. The experiment was undertaken firstly to provide information on the transport of sediment of various sizes and specific gravities and, secondly, to evaluate the use of the magnetic tracer. Attempts were made to relate the measured sediment transport rates to wave and wave-dependent parameters. Chapter 5 is concerned with a fluorescent tracing experiment undertaken to provide additional data on the transport of very fine sand. These data were combined with data from chapter 4 to again try and find relationships between sediment transport rates and wave-dependent parameters. Chapter 6 describes a fluorescent tracing experiment designed to investigate the possible transfer of coarse sediment from the nearshore seafloor to the foreshore of a mixed sand and gravel beach. Chapter 7 outlines an attempt to find and use an alternative tracer type that was suitable for tracing fine sediments in New Zealand. Chapter 8 evaluates both the practical application of the artificial tracer technique in nearshore sediment transport studies and the results from this study. Conclusions from the study are presented in Chapter 9 along with some suggestions for future research.

CHAPTER II

STUDY AREA AND THESIS AIMS

2.1 INTRODUCTION

Timaru, located on the east coast of the South Island, New Zealand (fig. 2.1) was chosen as the site for the present study. Timaru is an ideal location for a study of nearshore sediment transport for two reasons. Firstly, Timaru Harbour Board has a substantial interest in littoral drift in the area. This interest arises primarily because regular maintenance dredging is required to remove littoral drifted sediment from the harbour entrance channel. This sediment must then be disposed of and is currently dumped on the seabed to the north of the port. Timaru Harbour Board is also responsible for management of both the accreting sand beach in Caroline Bay and the mixed sand and gravel beach at South Beach where considerable quantities of littoral drifted sediments have been deposited since construction of the harbour began in 1878. Timaru Harbour Board has a longstanding research interest in littoral transport in the vicinity of the port and were willing and able to provide much of the logistic

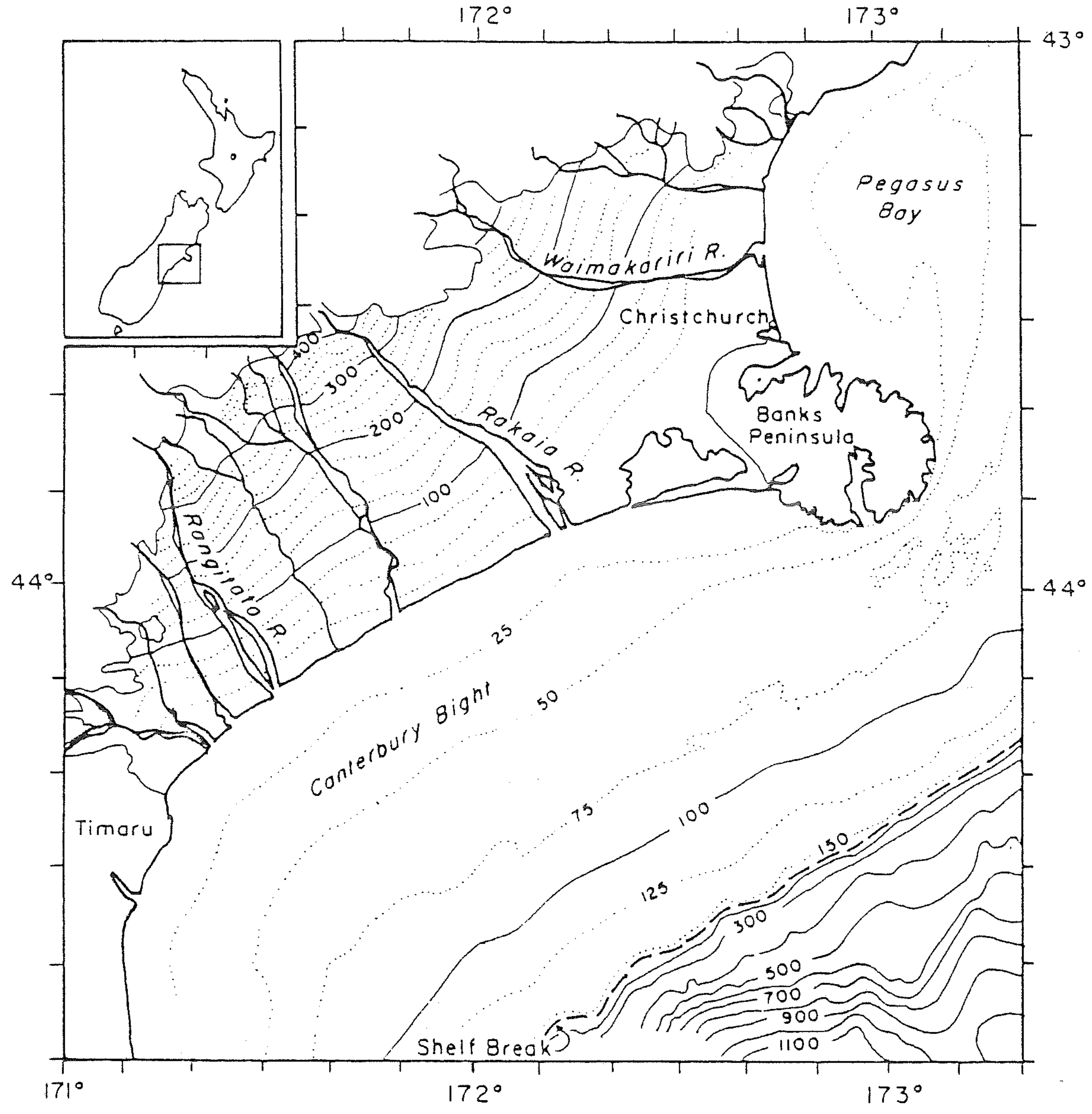


FIGURE 2.1 BATHYMETRY OF THE CONTINENTAL SHELF IN THE CANTERBURY BIGHT AND SIMPLIFIED PHYSIOGRAPHY OF THE ADJACENT LAND MASS. CONTOUR INTERVAL 25 m DOTTED LINES, 100 m SOLID LINES. ADAPTED FROM HERZER (1977, FIG. 2B, P.38).

and financial support required during the present study to enable offshore work to be carried out.

Secondly, a number of previous investigations of both scientific and applied types have been carried out in the area providing a good basis for more detailed studies. In particular, a considerable amount has become known about the beaches in the area but little is known in detail about the nearshore processes. A substantial amount of nearshore sediment transport is, however, known to occur.

All field work was carried out within the area outlined in figure 2.2. The area extends approximately 5 km north and 3.6 km south of Timaru Harbour to a distance of 5 km offshore. Water depths do not generally exceed 15 m. All of the processes under study are contained within this area and so the exact boundaries are unimportant. With one exception, all field work involved diving. All diving was carried out using SCUBA equipment (self contained underwater breathing apparatus).

2.2 THE TIMARU COASTAL ENVIRONMENT

The coastline surrounding Timaru is dominated by mixed sand and gravel beaches. Such beaches are comparatively rare on a world scale (Zenkovich 1967, p. 271) but are common in New Zealand. The beaches form part of an almost continuous stretch of mixed sand and gravel beaches extending 240 km southward from Banks Peninsula. At Timaru

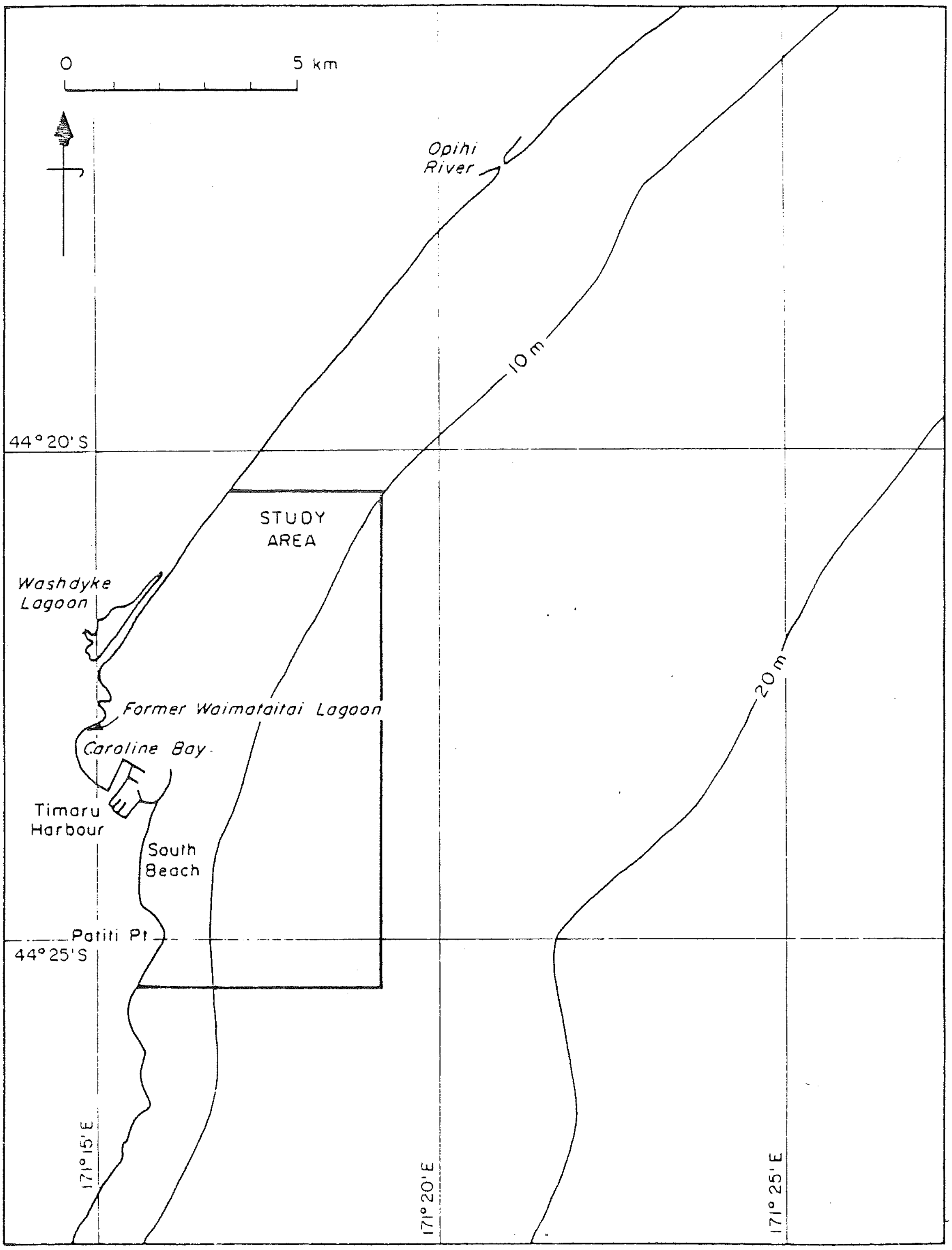


FIGURE 2.2   STUDY AREA.

this stretch of beaches is broken by 10 m high loess cliffs overlying an extensive basalt rock formation, a sandy beach in Caroline Bay, and Timaru Harbour.

The mixed sand and gravel beaches form the seaward margin of the southern half of the Canterbury Plains. The Plains consist of a series of giant alluvial fans built by the major rivers, the Rangitata, Rakaia and Waimakariri, during successive glaciations when great quantities of gravel were released into the river systems by the glaciers that occupied the mountain valleys (Fitzharris, Mansergh and Soons 1982). The simplified physiography of the Plains is shown in figure 2.1.

The arcuate shape of the 25 and 50 m isobaths in central and southern Canterbury Bight, shown in figure 2.1, was assumed by Herzer (1977) to represent the submerged extensions of the Rakaia and Rangitata outwash fans. The fans were inundated during the last post-glacial sealevel rise beginning approximately 17 000 yr BP and continuing until approximately 6000 yr BP (Kirk 1975b). Because the drowned fans are well defined between the 25 and 50 m isobaths it is assumed that drowning was initially rapid and little erosion occurred. The later stages of coastal retreat, however, involved a large amount of cliffing (Herzer 1977).

During the last 6000 yr the present coastline has been developed. The easily erodible nature of the alluvial fans backing the beaches combined with high longshore transport rates and high-energy waves has resulted in continuous erosion of the coast. Currently, the whole of the South Canterbury coast is thought to be eroding at average rates of 0.6 - 1.2 m yr^{-1} (Kirk 1979).

Figure 2.3 shows the typical morphology and zonation of a mixed sand and gravel beach. It can be seen from the profile that the beaches are narrow, steep (5 - 12°) and extend only a short distance below the low water mark where there is an abrupt change in gradient and sediment texture indicating the beginning of the continental shelf. Coarse sediment is confined to the nearshore face and landward while finer sediment is confined to the area seaward of the nearshore face. This separation of coarse and fine sediment was observed by the author when diving off South Beach. The separation was very marked although a few small patches of gravel could be found on the seafloor. The profile of the beach at this location conformed in general to the typical profile shown in figure 2.3 but was complicated by a number of humps and hollows on the nearshore face. The profile was observed during relatively calm conditions and its exact form was obviously a function of both these and the immediately antecedent conditions. The implications of a separation of coarse and fine sediments for nearshore sediment transport are discussed shortly.

The continental shelf in the Canterbury Bight is approximately 90 km wide with the shelf break, shown in figure 2.1, lying between the 150 m and 180 m isobaths, giving an average slope of approximately 0.1°. The shelf is mantled by modern, relict and palimpsest terrigenous

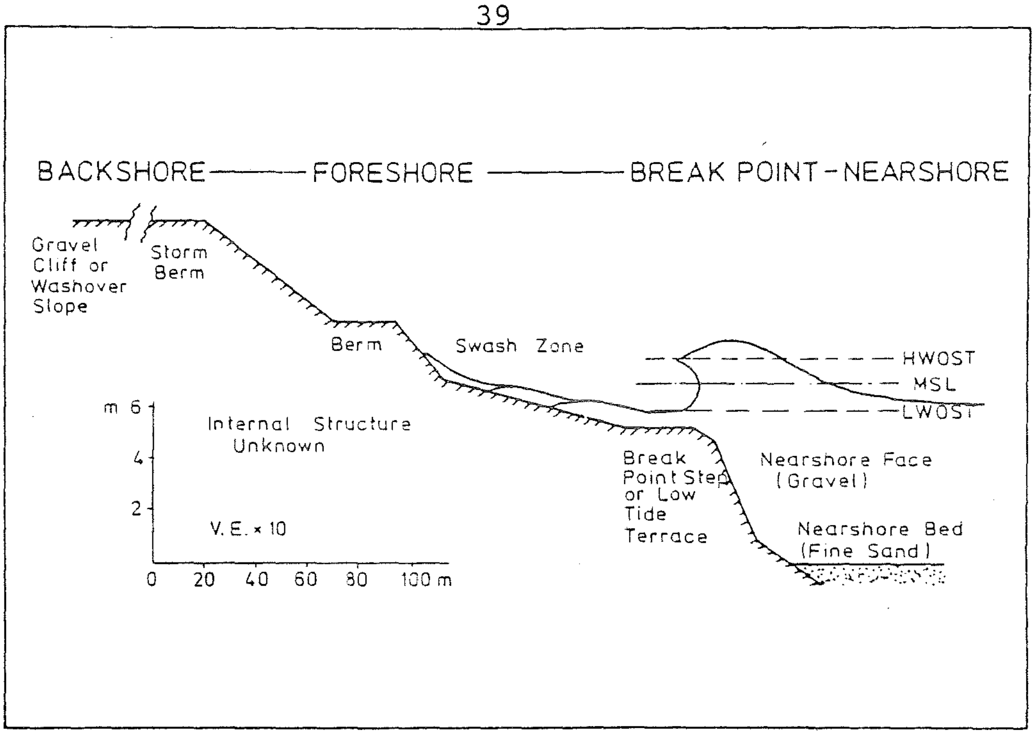


FIGURE 2.3 TYPICAL MORPHOLOGY AND ZONATION OF A MIXED SAND AND GRAVEL BEACH. FROM KIRK (1980).

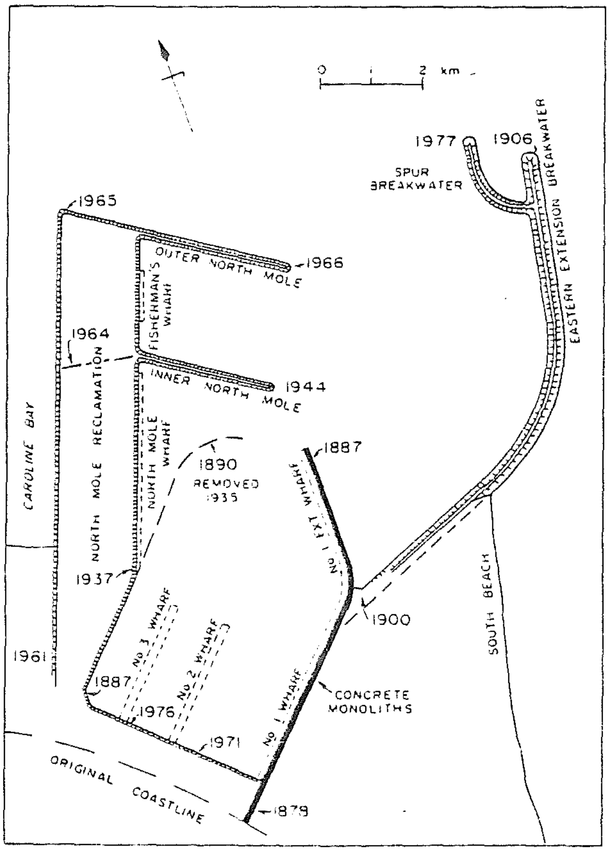


FIGURE 2.4 HISTORY OF PORT DEVELOPMENTS AT TIMARU. FROM TIERNEY AND SHEARS (1979).

sediments (Herzer 1977).

The coastline at Timaru is exposed to high-energy waves of an "east coast swell environment" (Davies 1964). There is unlimited wave fetch to the east and a maximum storm wave 7 - 8 m high can be expected 1 km offshore (Hydraulics Research Station 1970). The predominant wave direction is from the east to south-east quarter (Tierney 1977) and this causes a predominant northward movement of littoral sediments. Because of the well defined separation of coarse beach sediments and fine nearshore sands littoral transport functions as two separate and distinct sediment transport systems (Tierney and Kirk 1978). The first system involves the northward transport of coarse sediments on the beaches and the second system involves the northward transport of fine sediments on the nearshore seafloor. The transport system is dominated by longshore rather than on-offshore transport (Carter and Heath 1975). In this respect the littoral transport systems differ from the more common sand beach systems which experience periodic on-offshore transport of sand.

Both of the littoral transport systems at Timaru have been considerably altered since 1878 when construction of the breakwaters forming Timaru Harbour began. Prior to this time the port was operated as an open roadstead with ships anchoring offshore and surf-boats providing a landing service. The history of the port developments is summarised in figure 2.4. The various construction phases have been outlined by Clark (1921), Maxwell (1930), Hassall

(1955) and Tierney (1977). It is clear from these reports that early construction was dominated by the northward movement of beach gravel. In 1874 Sir John Coode, an eminent London engineer, was asked to formulate a plan for making a harbour at Timaru. Coode proposed that an artificial reef be built nearly parallel with the shoreline 400 m from shore. The southern end of the reef was to be connected with the shore by an open iron viaduct to allow the uninterrupted travel of gravel along the beach. This plan, however, was never adopted and instead a solid breakwater was constructed. Gravel began to accumulate behind the breakwater and threatened to move around the end and block the entrance to the port. One solution proposed at the time was to remove the gravel from the south beach with a "Priestman" grab and deposit it on the north beach. Although a crane was purchased for this purpose nothing further was done (Clark 1921). Instead, the breakwater was extended by construction of the Eastern Extension Breakwater.

While gravel accumulated to the south of the breakwater sand began accumulating in Caroline Bay. The sand began to drift into the harbour and in 1887 work commenced on a lee wall to protect the harbour from this drift and to provide added shelter. Subsequently this wall was realigned and extended by reclamation to form the North Mole (Tierney 1977).

Figure 2.5 shows the gravel accumulation behind the Eastern Extension Breakwater between 1909 and 1933. Because the breakwater was acting as a barrier to the

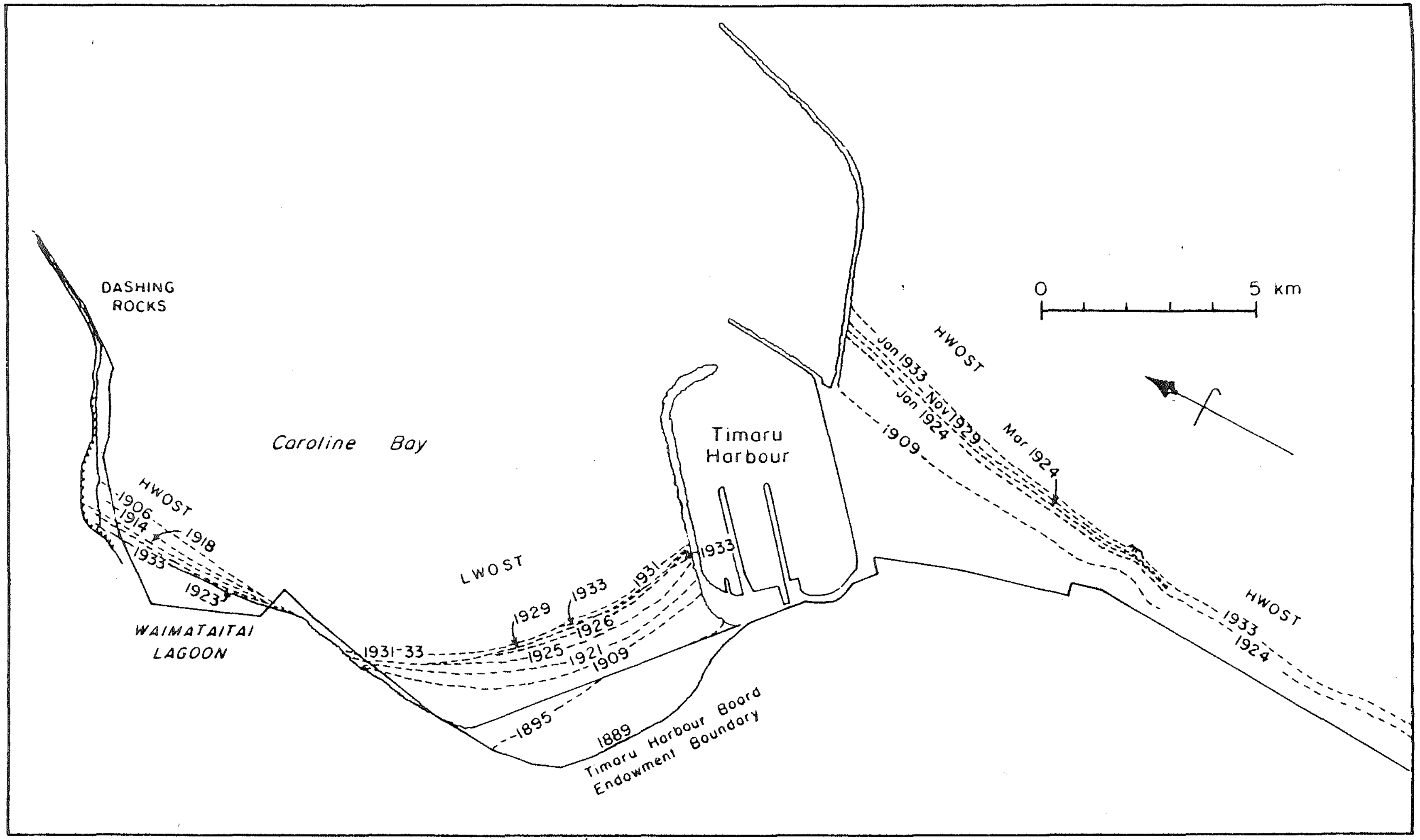


FIGURE 2.5 COASTLINE CHANGES IN THE VICINITY OF TIMARU HARBOUR FROM 1889 TO 1933. FROM NEW ZEALAND NAUTICAL ALMANAC, 1934. (MAP HELD IN THE MAP LIBRARY, DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF CANTERBURY, CHRISTCHURCH, N.Z.).

northward transport of beach gravels,beaches to the north of the harbour had their gravel supply substantially reduced. This resulted in increased erosion of these beaches, with the magnitude of the increase diminishing in a northward direction away from the harbour. The reason for the pattern is that the beach at any point to the north receives gravel supply from two principal sources. Owing to coastal retreat there is supply from direct erosion of the hinterland. This source provides less material in the south where the beach encloses Washdyke Lagoon. A second source is net northward longshore drift, so that locations further to the north receive materials from progressively greater lengths of feeder beach. The contribution of coarse sediment from offshore is unknown.

Initially the worst effects of the reduced gravel supply occurred at Waimataitai Lagoon where the barrier beach was continually eroded until during the 1930's it was breached and the lagoon was lost. The retreat of the barrier between 1906 and 1933 is shown in figure 2.5. Further north the beach enclosing Washdyke Lagoon was also eroding rapidly and has continued to do so. The supply of gravel to this beach has decreased with time as less material is transported northward from Waimataitai and this has resulted in an accelerating erosion rate, as shown in figure 2.6. Figure 2.7 shows the retreat of the coastline at Washdyke between 1849 and 1978. This diagram also shows the accumulations of both very fine sand in Caroline Bay and gravel behind the Eastern Extension

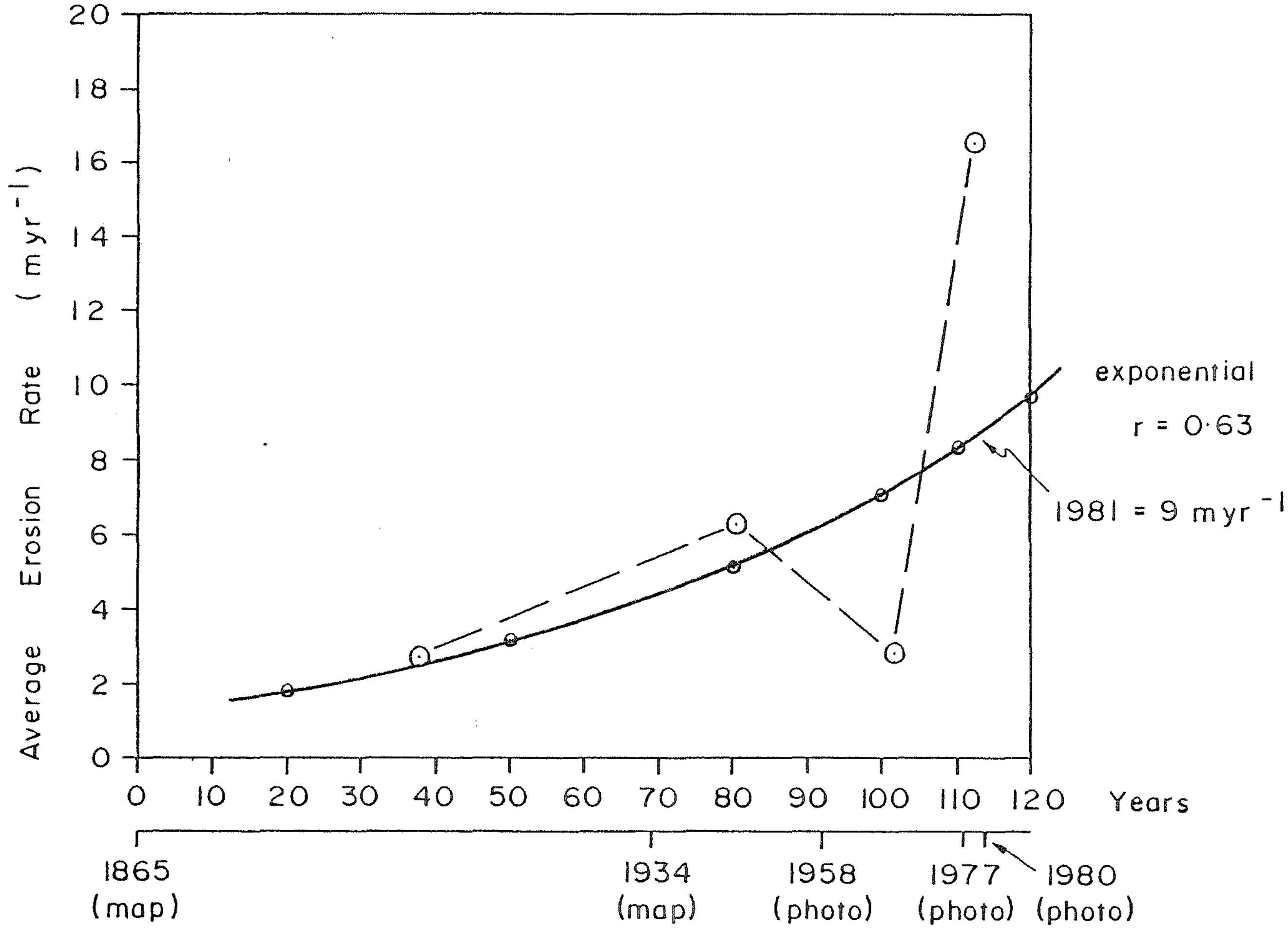


FIGURE 2.6 RATES OF COASTAL EROSION AT WASHDYKE BEACH 1865 TO 1981. FROM KIRK (1981)

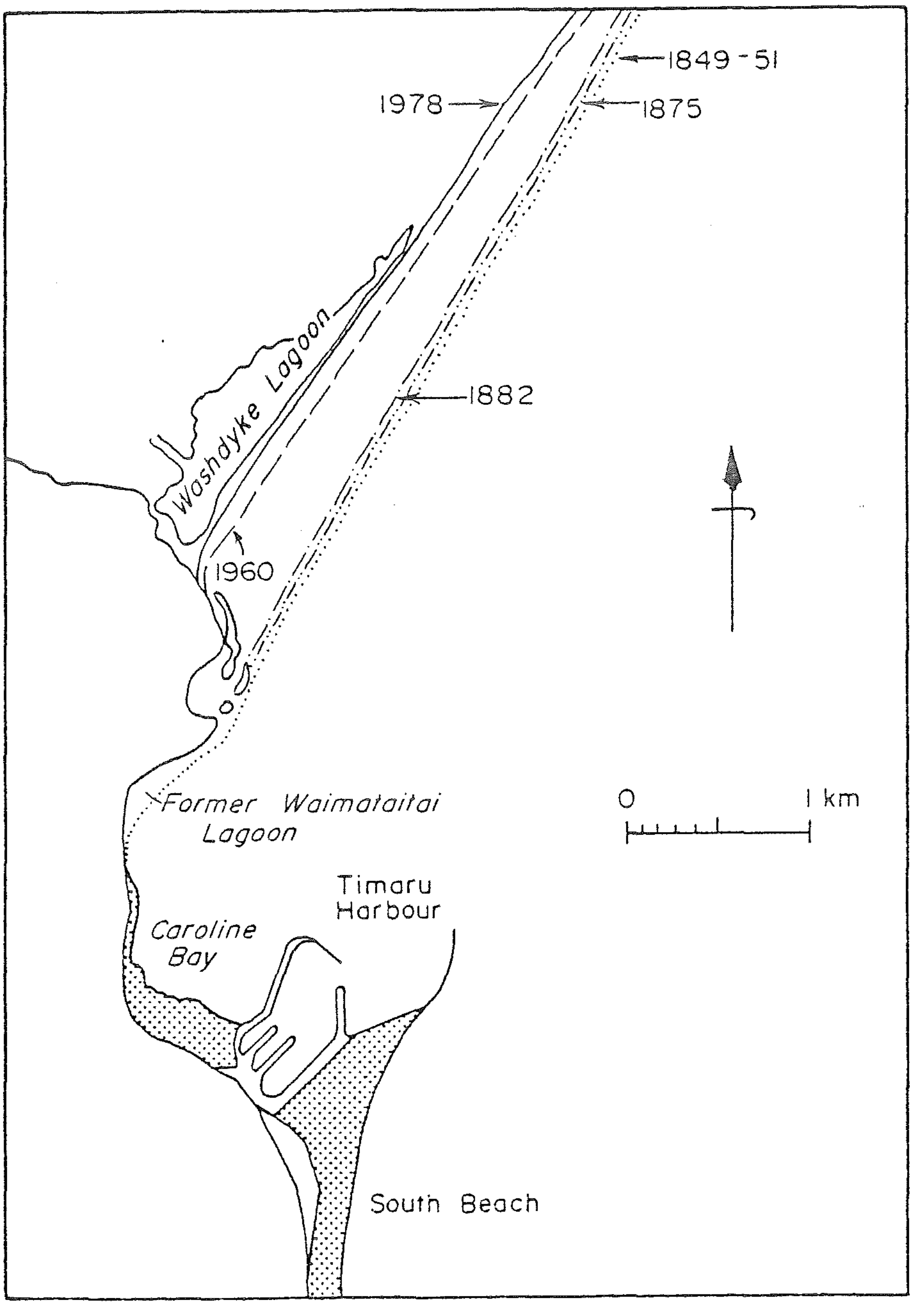


FIGURE 2.7 RETREAT OF THE COASTLINE AT WASHDYKE FROM 1849 TO 1978. THE SHADED AREAS INDICATE THE ACCUMULATIONS OF SAND IN CAROLINE BAY AND GRAVEL AT SOUTH BEACH OVER THE SAME PERIOD. FROM KIRK (1983).

Breakwater at South Beach since construction of the harbour began in 1887.

Two other factors have been important in modifying the northward littoral drift of sediment. The first of these is gravel extraction from South Beach where an estimated 580 000 m^3 was removed between 1879 and 1967 (Tierney 1977). The second factor is dredging of the harbour entrance channel. Since dredging began in the 1880's 12 000 000 m^3 of material has been removed and the bulk of this has been dumped 3 km to the north of the port and 1.5 km offshore (Tierney 1977, 1982).

In summary, the situation at Timaru today is:

a) Northward moving beach gravels are trapped behind the Eastern Extension Breakwater. Timaru Harbour Board attempts to prevent further growth of the beach in this area by licensing gravel extraction to balance the accumulation. Recent observations indicate that the beach has reached a quasi-equilibrium state, only changing in response to changing wave conditions (Tierney 1977). Some gravel, however, may move around the breakwater and become deposited in the port entrance channel.

b) Very fine sand on the nearshore seafloor is transported predominantly northward. An estimated 17% of this material is trapped by the entrance channel (Tierney and Kirk 1978). Maintenance dredging of this channel required the removal of an average 106 300 m^3 yr^{-1} between 1966 and 1976 (Tierney and Kirk 1978). This material was dumped to the north of the port.

c) Sand is continuing to accrete in Caroline Bay at an average rate of 30 500 m^3 yr^{-1} (Tierney 1977). The shoreline is advancing seaward at an average rate of 3.4 m yr^{-1} and if no action is taken to halt the accretion it seems likely that the Bay will eventually fill up.

d) Erosion is continuing on the beaches to the north of the port, decreasing in severity with increasing distance northward. The most seriously affected stretch at present is the barrier beach enclosing Washdyke Lagoon. In 1981 an erosion rate of 9 m yr^{-1} was measured (Kirk 1981). Unless some action is taken to halt the erosion the loss of the barrier beach is a distinct possibility within the next two decades (Kirk 1979). The lagoon acts as the outlet for a coastal drainage network which services the low lying land behind the coast, is a wildlife refuge and the barrier beach supports the Timaru City sewer outfall. Loss of the lagoon would therefore have serious consequences for the Timaru area. In 1978 and 1979 discussions were held between Timaru Harbour Board, Timaru City Council and South Canterbury Catchment Board regarding erosion at Washdyke. Timaru City Council decided to investigate the use of beach renourishment to reduce the erosion at Washdyke and Timaru Harbour Board agreed to investigate the effectiveness of providing beach renourishment by dumping dredged material offshore (Tierney 1982). In 1980 Timaru City Council undertook a trial beach renourishment scheme at Washdyke. A 300 m long section of beach was renourished by re-forming the rear and crest of the beach by bulldozing and then adding a capping of hard fill. Since its construction a detailed and comprehensive monitoring program has been maintained by Timaru City Council (Kirk 1981). To date the trial has proved very successful in reducing the retreat of the beach and in allowing the effectiveness of this type of protection to be evaluated (Kirk 1981). Also in 1980, Timaru Harbour Board agreed to support the present study of nearshore sediment transport in the vicinity of the harbour with a view to using the information gained to help assess the effectiveness of an offshore beach renourishment operation using dredged material.

2.3 PREVIOUS STUDIES

There have been a number of recent studies made of the South Islands mixed sand and gravel beaches. These include work by Kirk (1967, 1970, 1975a), McLean and Kirk (1969), Armon (1970, 1974), Pickrill (1973), Kelk (1974) and Hewson (1977). This work has concentrated on morphology and sediment characteristics, process regimes, profile responses and sediment - morphology interaction and the findings are reviewed in a recent article by Kirk (1980).

Estimates of littoral transport rates at Timaru can be found as early as 1890. Blair (1890) reported that experiments at Timaru had shown that beach gravel could travel up to 1.6 km day^{-1}. He also reported that within 9 years of completion of the first breakwater 917 000 m^3

of gravel had been intercepted. This is equivalent to an average annual rate of approximately 102 000 m^3 yr^{-1}.

Clark (1921), a Timaru Harbour Board engineer, was the next to present littoral transport rates. In his paper he presents three estimates of the annual accumulation rate behind the breakwater. The first estimate of 76 000 m^3 yr^{-1} was made by a previous engineer. The second estimate of 58 000 m^3 yr^{-1} was made by Clark himself from measurements of the accumulated gravel. The third estimate, attributed to other engineers, was 67 000 m^3 yr^{-1}. Clark also presents figures for the amount of accumulation in Caroline Bay. From 1880 to 1920 2 300 000 m^3 of sand had accumulated at an average annual rate of 57 000 m^3 yr^{-1}. A slightly lower rate of 51 000 m^3 yr^{-1} was indicated by soundings over the previous three years. Clark lists the rate of seaward movement of the low water contour as about 2.4 m yr^{-1} during a period of 12 years.

Maxwell (1930) was the first person to attempt to measure the total drift passing Timaru, including fine sand, silt and gravel. He studied cross sections of the coastline between Timaru and Washdyke, which extended over long periods, and made observations of the changes to the north of the port for over 2 years. Maxwell then concluded that the total drift, including gravel, could not be less than 400 000 m^3 yr^{-1}. Of this figure Maxwell thought that about 10% or 40 000 m^3 yr^{-1} consisted of gravel and the other 90% or 360 000 m^3 yr^{-1} consisted of sand and silt.

Tierney (1969, 1977) calculated the quantity of littoral drift material moving past the port by considering the accumulations at South Beach and in Caroline Bay, the quantities of gravel extraction and the amount of dredging to remove siltation material. He concluded that the average minimum annual littoral drift from 1879 to 1967 was 206 000 m^3 yr^{-1}, approximately 30% of which was beach gravel with the remaining 70% being finer material on the seafloor. This figure did not include any material moving as suspended load.

All of these studies on littoral drift, with the exception of the experiment on beach gravel movement reported by Blair (1890), have calculated quantities from long-term data on accumulation rates, dredging and profile changes. In 1977 a new approach was taken in a two-part study of sand transport processes on the nearshore seabed adjacent to the port. This study is reported by Kirk (1977, 1978) and by Tierney and Kirk (1978). The first part of the investigation involved a sediment survey to define surface sediment texture and used "rollability analysis" to infer sediment transport paths. The second part of the investigation involved carrying out a sand tracing experiment to determine both the directions and rates of sand transfer on the seabed 3 km to the north-east of the port.

Results from the sediment survey are summarised in figure 2.8. This diagram shows that the seafloor is mantled with a very uniform layer of fine and very fine

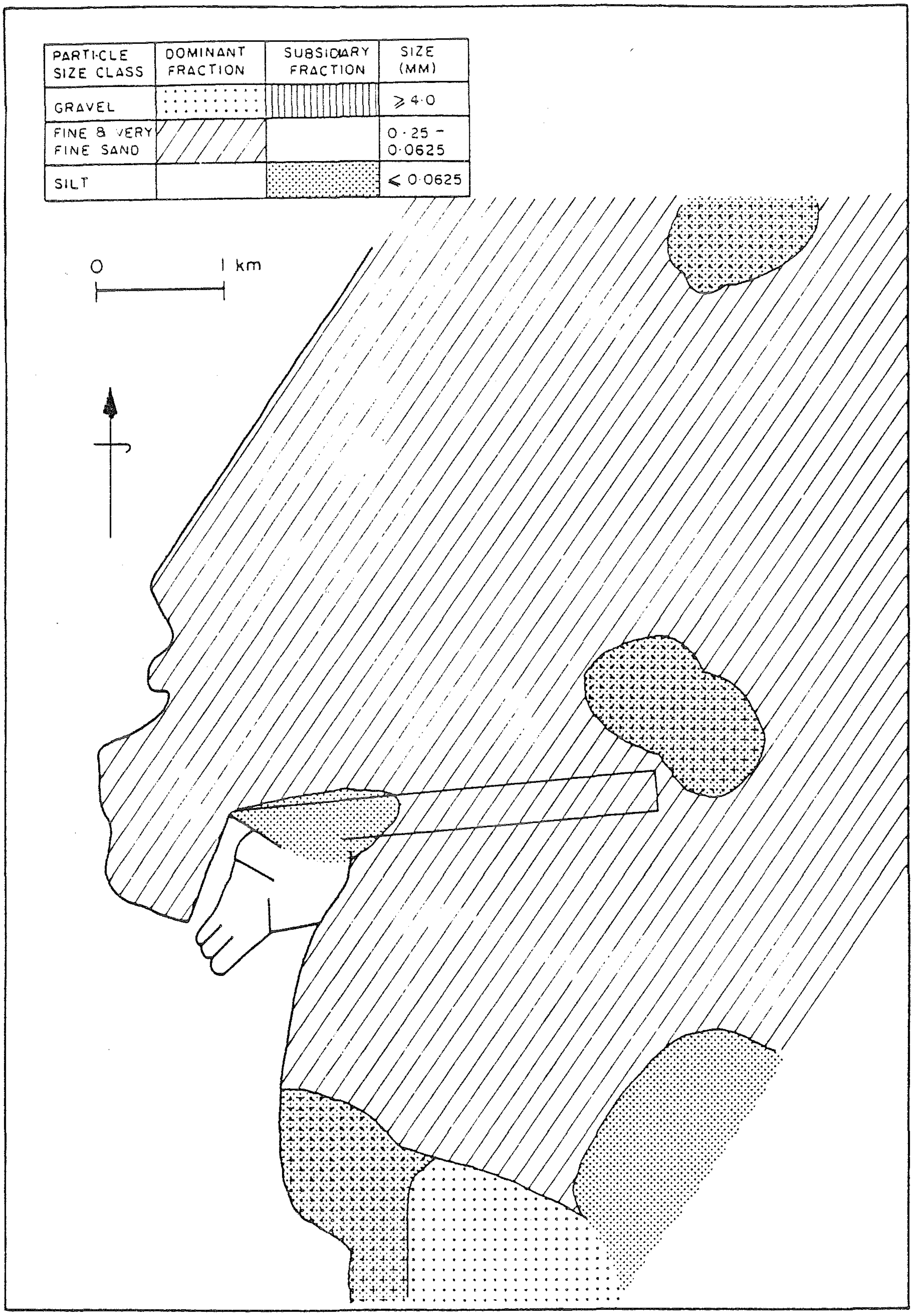
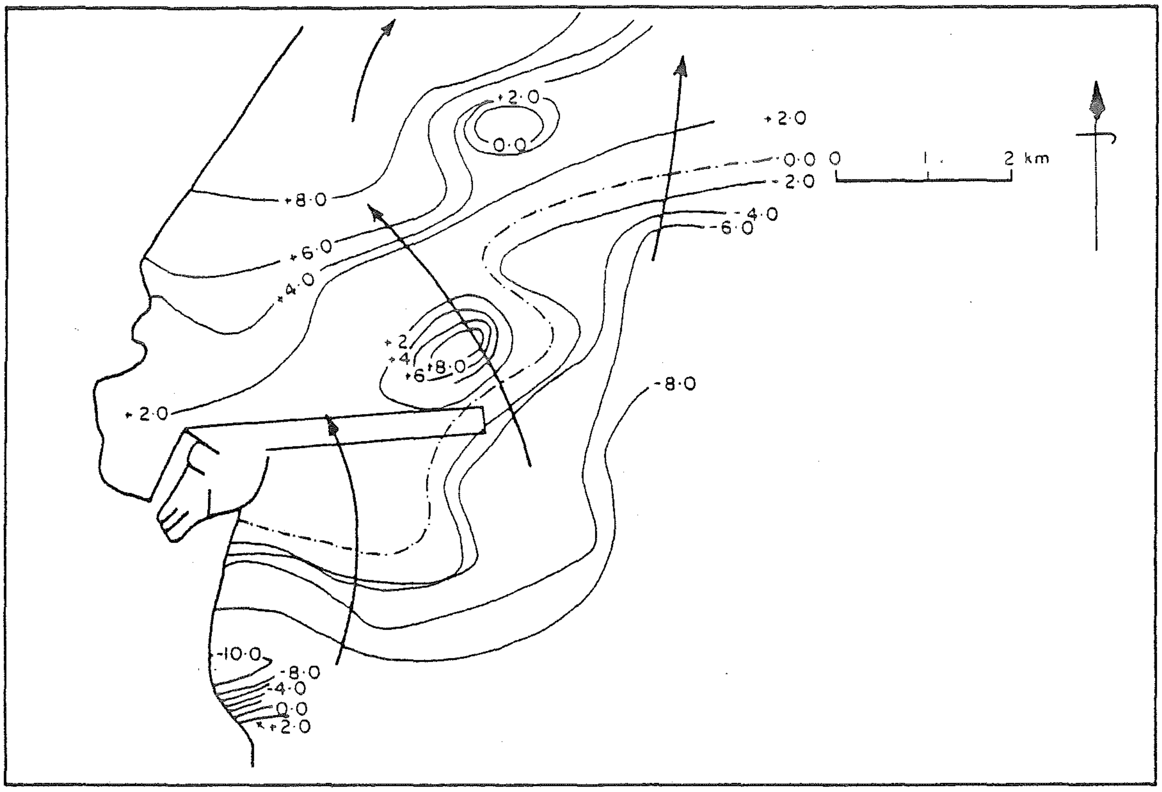


FIGURE 2.8 SEAFLOOR SURFACE TEXTURE FROM KIRK (1977).

sand with an occasional patch of gravel or silt. Rollability analysis was performed on the fine fractions (1.0 mm - 0.053 mm) of all samples possessing appreciable sand. Rollability is a functional measure of sand-grain shape and it has been correlated with the processes of erosion, transportation and deposition of sediment in wind tunnels, flumes, wave tanks and a variety of field environments (Winkelmolen 1969). The rollability value for a given sample is taken as the median time for that sample to travel through a smooth-walled, inclined, rotating cylinder. By controlling for size by sieving it is possible to compare the rollability values obtained from a number of samples and to calculate relative rollability values by expressing each individual value as a relative deviation from the average value for that size. It is then possible to discover whether there are places where relatively more rollable and relatively less rollable grains are concentrated. This assists in establishing the sites of sources and sinks of sediment, and can identify major transport vectors between them although no information on quantities or rates of transport are obtained.

Figure 2.9 shows the relative rollability values for one of the coarser sand fractions (0.355 mm) and for a very fine sand fraction (0.075 mm). Negative values indicate areas where grains were relatively less rollable and hence more transportable. They therefore indicate sediment sinks. Positive values indicate areas where grains were relatively more rollable and hence less

(a)



(b)

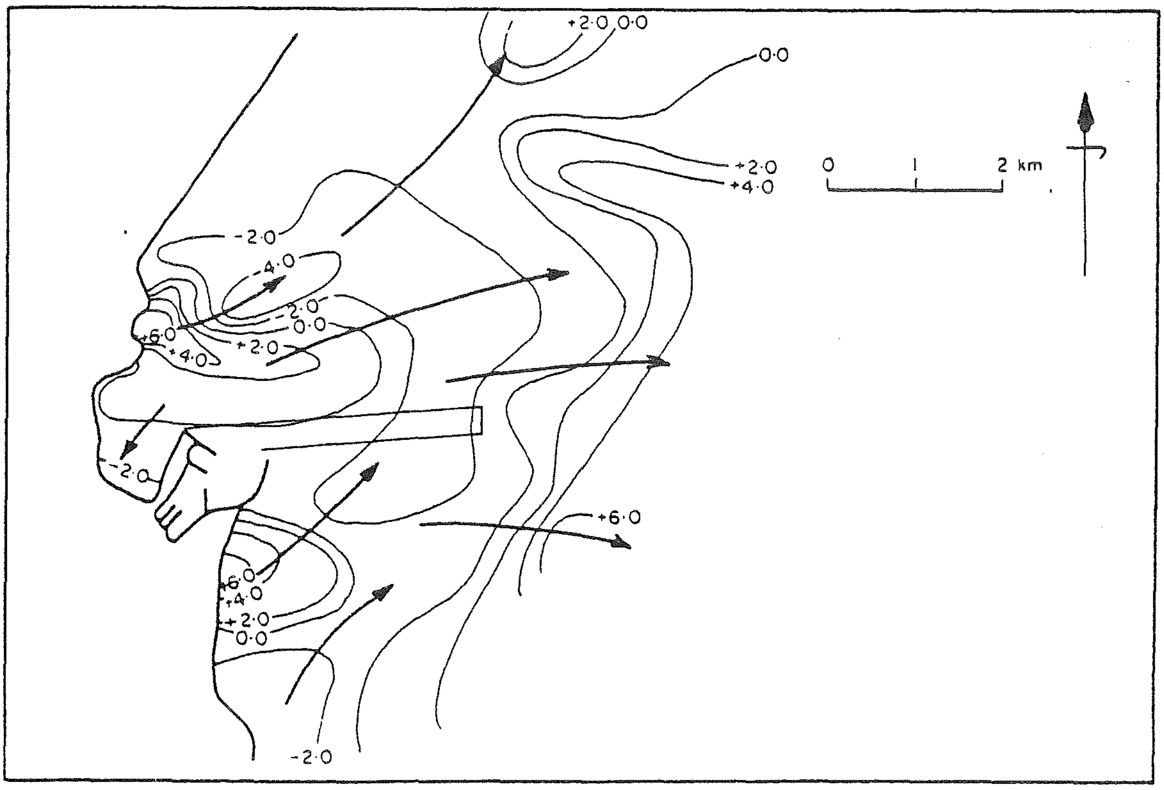


FIGURE 2.9 RELATIVE ROLLABILITY VALUES FROM KIRK (1977).

(a) MEDIUM SAND (0.355 mm)

(b) VERY FINE SAND (0.075 mm)

transportable. They therefore indicate sediment sources. The transport vectors inferred from the rollability values are shown by the arrows on the diagram. It can be seen that an inshore movement of the coarser sand particles and a simultaneous offshore diffusion of the finer sand were indicated. Both of these processes are superimposed on the northward regional drift.

For the second part of the investigation approximately 100 kg of sand was obtained from the foreshore of Caroline Bay and air dried. Approximately 83 kg of this sand was then mixed in 10 kg lots in an electrically driven concrete mixer with "Neozapon Blue FLE" dye and a solvent. It was then air dried and bagged.

Because tracer movement was to be determined by the spatial integration method a rope grid was constructed to enable accurate positioning of samples. The grid, of radial configuration with a maximum length of 40 m, was placed on the seafloor and the dyed sand released at the central point. Samples from the grid were collected on three occasions (3.0 h, 21.5 h and 92.5 h) following the release of the dyed material. The samples were collected in 15 cm long 50 mm diameter tubes which were pushed into the bottom in a scooping motion.

Concentrations of dyed grains in each sample were calculated by counting small sub-samples in polarised light on a "Wild Petrographic Microscope". The tracer transport rate was calculated only for the final sampling run after 92.5 hours had elapsed. In the calculation it was assumed that the depth of the mobile layer was 0.10 m. This figure was estimated from burial patterns as indicated by the dispersion diagrams in conjunction with estimates from other studies. A unit width transport rate of 0.46 $m^3\ m^{-1}\ day^{-1}$ in the north-west direction was calculated. By assuming that transport rates of this order characterised all the seabed off Timaru to at least the 11 m isobath the total transport through the area enclosed by the 11 m isobath (which is 3.5 km offshore) was calculated as 1610 $m^3\ day^{-1}$. This converts to a mean annual northward transport of 587 650 $m^3\ yr^{-1}$. Because southward transfers were on average about 10% of the main movements the total mean annual transfers past the port on the nearshore seafloor were thought to be of the order of 650 000 $m^3\ yr^{-1}$. Tierney and Kirk (1978) summarised these and other results by presenting a schematic average annual sediment budget, reproduced here in figure 2.10.

Gibb and Adams (1982) have attempted to produce a sediment budget for the South Island east coast between Oamaru and Banks Peninsula. By considering inputs from rivers and cliffs, and losses by abrasion, Gibb and Adams estimated that $2.16 \times 10^6\ m^3\ yr^{-1}$ of suspended load, including very fine sand and mud, moves northward past Timaru. This rate is not directly comparable with the rate calculated by Kirk (1978) because of the different transport zone widths used. The rate calculated by Kirk was for a zone extending from shore out to the 11 m

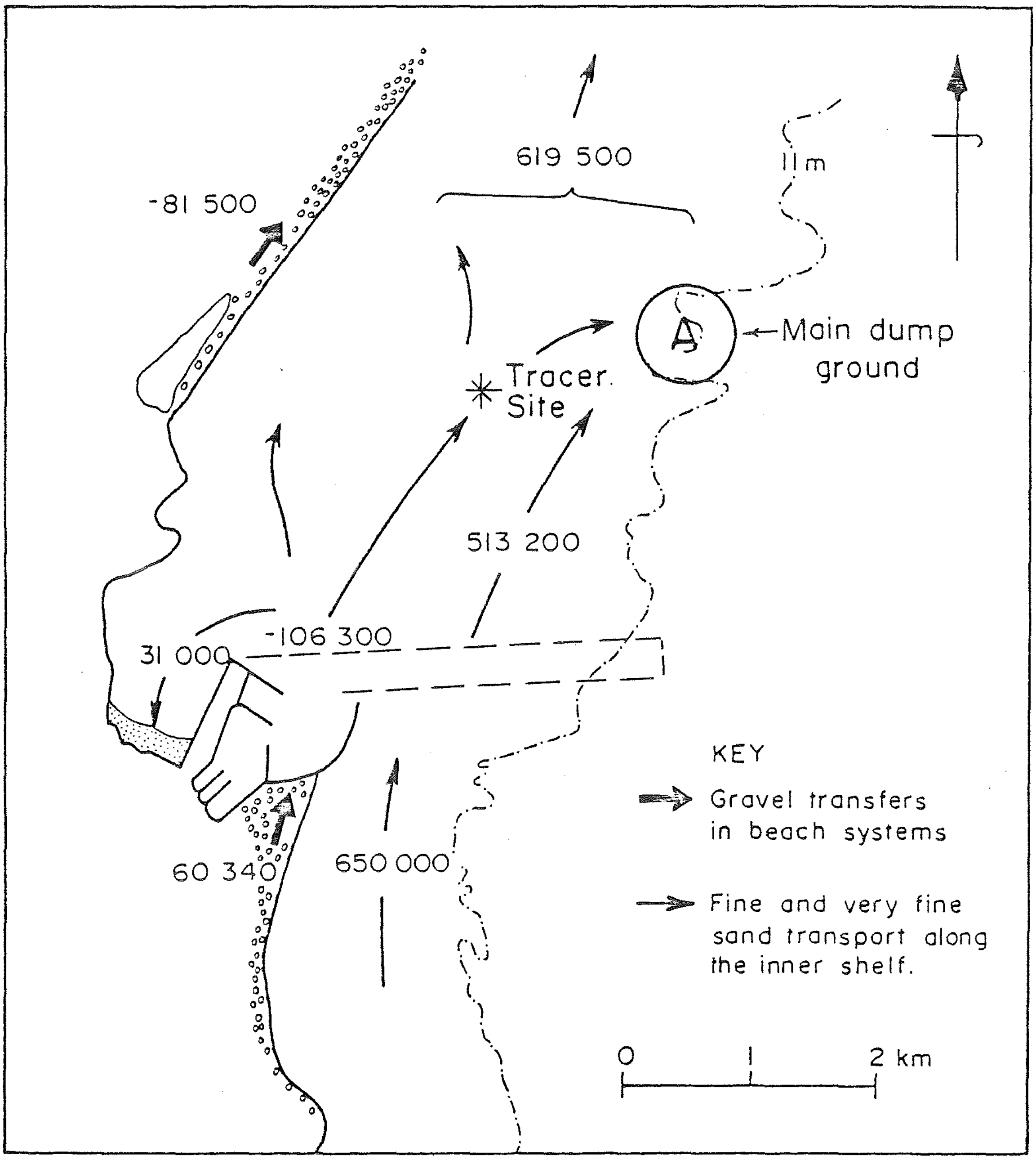


FIGURE 2.10 SCHEMATIC AVERAGE ANNUAL SEDIMENT BUDGET FROM TIERNEY AND KIRK (1978).

isobath whereas the zone used by Gibb and Adams extended from shore out to depths of 30 - 60 m. The transport rate calulated by Gibb and Adams is, however, 3.3 times greater than Kirk's rate and it seems unlikely that the different transport zone widths could account for a difference of this magnitude. Inspection of Gibb and Adams transport rate of 2.16×10^6 m^3 yr^{-1} reveals that 70% was derived from the suspended yield of rivers, 4% from cliff erosion and 26% from abraded beach gravels. Of the river yield 84% was derived from the Waitaki River. No other published suspended sediment yields could be located for the Waitaki River. However, further north Gibb and Adams estimated the annual suspended sediment yield for the Rakaia River as 8.56×10^6 t yr^{-1}. Griffiths (1981), on the other hand, estimated the annual suspended sediment yield for the Rakaia River as 4.33×10^6 t yr^{-1}. This suggests that the suspended sediment load inputs from rivers used by Gibb and Adams may be too high, which would explain their high sediment transport rate.

The various littoral transport estimates have been summarised in table 2.1. The largest range of estimated values occurs for the northward drift of fine sediment where the largest estimate is 15 times greater than the smallest estimate. This range of values is not surprising and highlights the difficulty of measuring sediment transport rates in the nearshore. Because the accumulations at South Beach and in Caroline Bay can be measured directly there is a lower range in the estimated littoral transport into these areas.

TABLE 2.1 LITTORAL TRANSPORT ESTIMATES AT TIMARU.

a) Accumulation Of Gravel At South Beach

REFERENCE		RATE $m^3\ yr^{-1}$	COMMENTS
Blair (1890)		102 000	
Clark (1921)	1	76 000	Estimated by a previous engineer
	2	58 000	Estimated by Clark
	3	67 000	Estimated by other engineers
Maxwell (1930)		40 000	
Tierney (1977)		60 000	Average rate between 1879 and 1967

b) Accumulation Of Sand In Caroline Bay

REFERENCE		RATE $m^3\ yr^{-1}$	COMMENTS
Clark (1921)	1	57 000	Average rate between 1880 and 1920
	2	51 000	Average rate between 1918 and 1920
Tierney (1977)		31 000	Average rate between 1879 and 1967

c) Northward Drift Of Fine Sediment On The Seafloor

REFERENCE	RATE $m^3\ yr^{-1}$	COMMENTS
Maxwell (1930)	360 000	
Tierney (1977)	144 000	Average minimum littoral drift of fine seafloor material from 1879 to 1967)
Kirk (1978)	650 000	Bedload transport out to the 11 m isobath
Gibb & Adams (1982)	2 160 000	Suspended load out to 30 - 60 m water depth

From this brief review of previous coastal sediment studies at Timaru the following points emerge:

a) A considerable amount of information exists on the behaviour of mixed sand and gravel beaches and on the littoral transport of beach gravels.

b) Much less is known about the transport of very fine sand on the seafloor. There has been only one attempt to measure the rate and direction of transport of very fine sand on the seafloor and this study was of short duration.

c) Nothing is known about the transport of coarser sediments on the seafloor, although a sediment survey showed that some patches of gravel did exist.

d) The morphology and texture of the system implies that coarse sediments remain onshore or are transported onto it while finer sediments remain on the seafloor. It is not known why this separation occurs or how it is maintained.

e) On-offshore exchange of sediment between the beach and the seafloor is thought to be minimal but has not been studied in detail.

f) The separation of littoral transport into two separate systems and the behaviour of each presents quite a different situation to that commonly found in the literature for sand beach systems.

A detailed study of nearshore sediment transport at Timaru could therefore not only provide additional information on the rates and directions of littoral transport in the area but could also provide valuable information on the functioning and maintenance of an unusual littoral transport system.

2.4 THESIS AIMS

Bearing in mind the previous discussions of the Timaru coastal environment and the discussions of wave-induced nearshore sediment transport and the artificial tracing technique in chapter 1, some specific aims were formulated. These were:

a) To determine the potential for nearshore sediment transport in the field area by studying in detail bathymetry, surface sediments, hydraulic conditions and depth of disturbance of sediment.

b) To determine the rates and directions of movement of sediments of various sizes and specific gravities.

c) To compare the movement of the various sediments studied.

d) To find relationships between measured transport rates and wave or wave-dependent parameters.

e) To investigate the possible transfer of sediment from the nearshore seafloor to a mixed sand and gravel beach.

f) To find an alternative artificial tracer type that could be used to study the movement of fine nearshore sediments in New Zealand.

g) To evaluate the results from the tracer studies with respect to long-term sediment transport rates in the field area.

h) To consider the applied aspects of any data obtained.

i) To evaluate the practical application of artificial sediment tracers in the study of nearshore sediment transport.

The remainder of this thesis seeks to realise these aims, beginning in the following chapter with a review of the nearshore environment and the potential for sediment transport in the study area.

CHAPTER III

THE NEARSHORE ENVIRONMENT

3.1 INTRODUCTION

This chapter begins by describing in detail aspects of the nearshore environment at Timaru that are important with respect to seabed sediment transport. These aspects are bathymetry, surface sediments, hydraulic conditions and depth of disturbance of sediment. This information is then used to assess the potential for nearshore sediment transport in the study area. This includes the calculation of the seaward limit of intense sediment transport and the percentage of time threshold velocities are exceeded.

3.2 BATHYMETRY

The bathymetry of the inner continental shelf around Timaru has been comprehensively surveyed only once, in 1959, by the Hydrographic Branch of the Royal New Zealand Navy. The results from this survey were used to produce

New Zealand Hydrographic Chart No. 6422 which is divided into two sections, "Approaches To Timaru" and "Timaru Harbour". The soundings are presented in fathoms and feet out to 11 fathoms and from then on in fathoms only. The datum to which the soundings are reduced is zero on the tide gauge at Timaru Harbour. Table 3.1 shows the relationship between chart datum and tidal levels at Timaru.

TABLE 3.1 RELATIONSHIP BETWEEN CHART DATUM AND TIDAL LEVELS AT TIMARU (FROM NEW ZEALAND HYDROGRAPHI CHART NO. 6422).

Height Above Datum Of Soundings

High Water		Low Water	
Mean Springs	Mean Neaps	Mean Springs	Mean Neaps
7.3 ft	6.7 ft	1.6 ft	2.3 ft
2.2 m	2.0 m	0.5 m	0.7 m

The section of the hydrographic chart covered by the study area is shown in figure 3.1(a) with all soundinc converted to metres.

A copy of the original fair sheet containing all of the soundings made for the "Approaches To Timaru" section of the hydrographic chart was obtained from the Navy. From this fair sheet it was possible to construct a bathymetric map of the study area, with the exception of the inshore area around the port (not shown on the fair

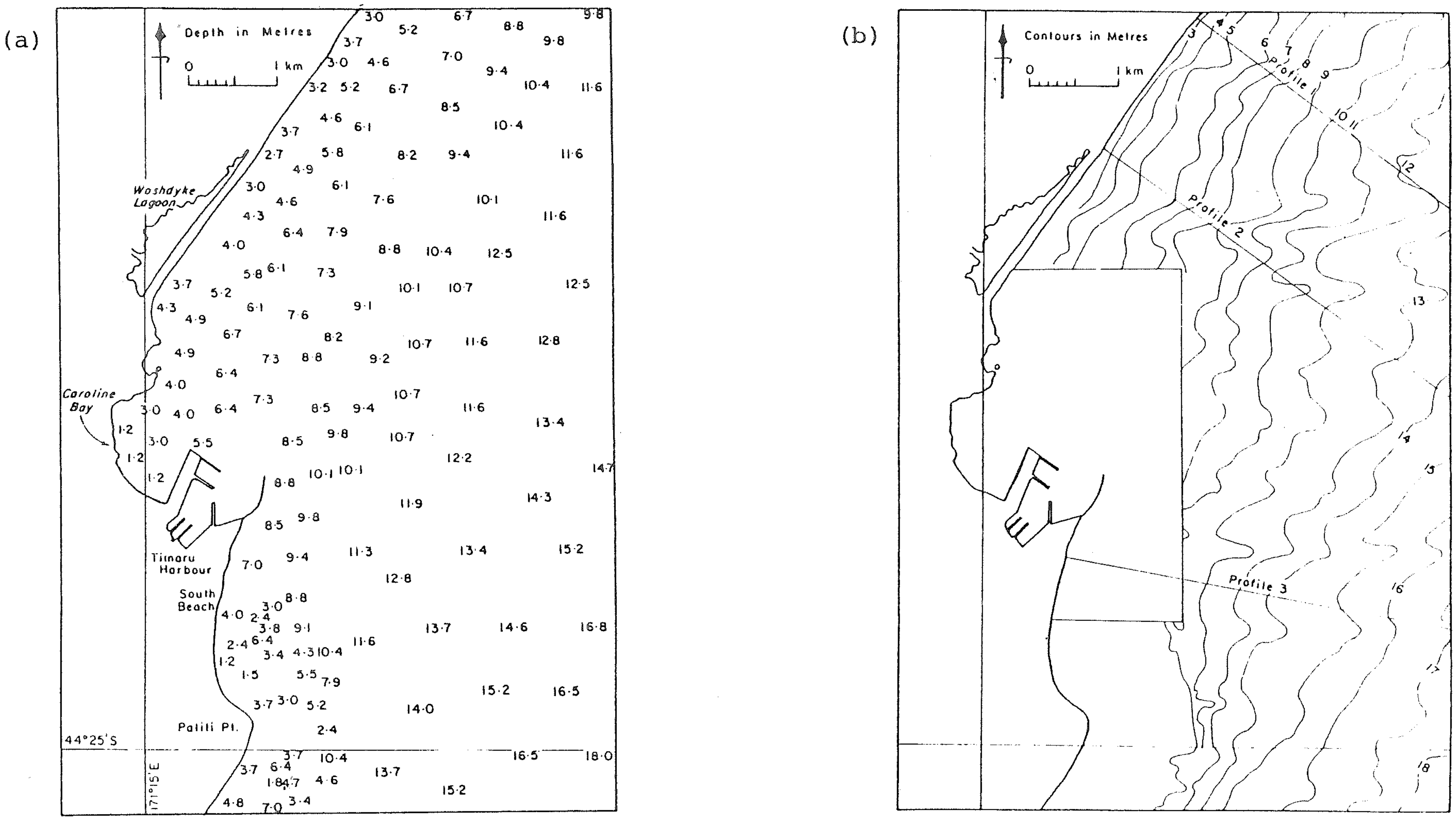


FIGURE 3.1

(a) HYDROGRAPHIC CHART FOR THE STUDY AREA.

(b) BATHYMETRIC CHART FOR THE STUDY AREA WITH THE LOCATION OF THE THREE PROFILES SHOWN IN FIGURE 3.2.

sheet) and the reef area to the south of the port. The resulting chart is shown in figure 3.1(b). In general, the isobaths shown on this chart are aligned approximately north-east/south-west which is parallel to the coastline from Washdyke northwards. To the south of the port the coastline projects further eastward and is aligned almost north/south. Isobaths in this area occur relatively closer to shore, indicating greater water depths than to the north of the port.

There is some quasi-regular longitudinal variability in the isobaths which may indicate the presence of large scale bedforms such as sand waves. A recent side-scan sonar survey at Timaru, undertaken by the New Zealand Oceanographic Institute, revealed no major relief on the seabed (Dr L Carter, New Zealand Oceanographic Institute 1982, pers. comm.). The survey did find irregular but commonly linear patches of acoustically light and dark sediment aligned about north-east/south-west. These patches were thought to be probable exposures of substrate beneath the discontinuous layer of fine sand (Dr L Carter, New Zealand Oceanographic Institute 1982, pers. comm.). It seems likely, therefore, that some type of sand waves do exist but that they are of small amplitude and beyond the ± 0.25 m resolution of the side-scan sonar used by the New Zealand Oceanographic Institute.

Another feature visible in figure 3.1(b) is that the isobath spacing increases with distance from the shore. This means that the gradient of the nearshore profile decreases with distance from shore. To investigate the shape of the profile more clearly three cross-sections were constructed from figure 3.1(b), in the positions indicated on this diagram. For profile 3 it was necessary to use data from the hydrographic chart for the inshore area.

The three profiles are shown in figure 3.2, all drawn on the same axes to allow easy comparison. The greater depth to the south of the port is clearly seen when comparing profile 3 with profiles 1 and 2, but despite this difference the profiles all have the same form. Initially, there is a steep gradient down from the coast and then a flattening of the profile with increasing distance from shore. The exact form of the profile closely adjacent to the shore cannot be determined from the information available. For profiles 1 and 2 the shallowest depth available was 3 m while for profile 3 no information was available shorewards of the 7 m isobath. This reflects the morphology of the area where there are steeply sloping beaches extending only a short distance seaward of the low water line and which give way to the more gently sloping continental shelf. It is not possible to obtain soundings over the submarine beach because of wave activity, the close proximity to shore, and the steeply sloping bottom.

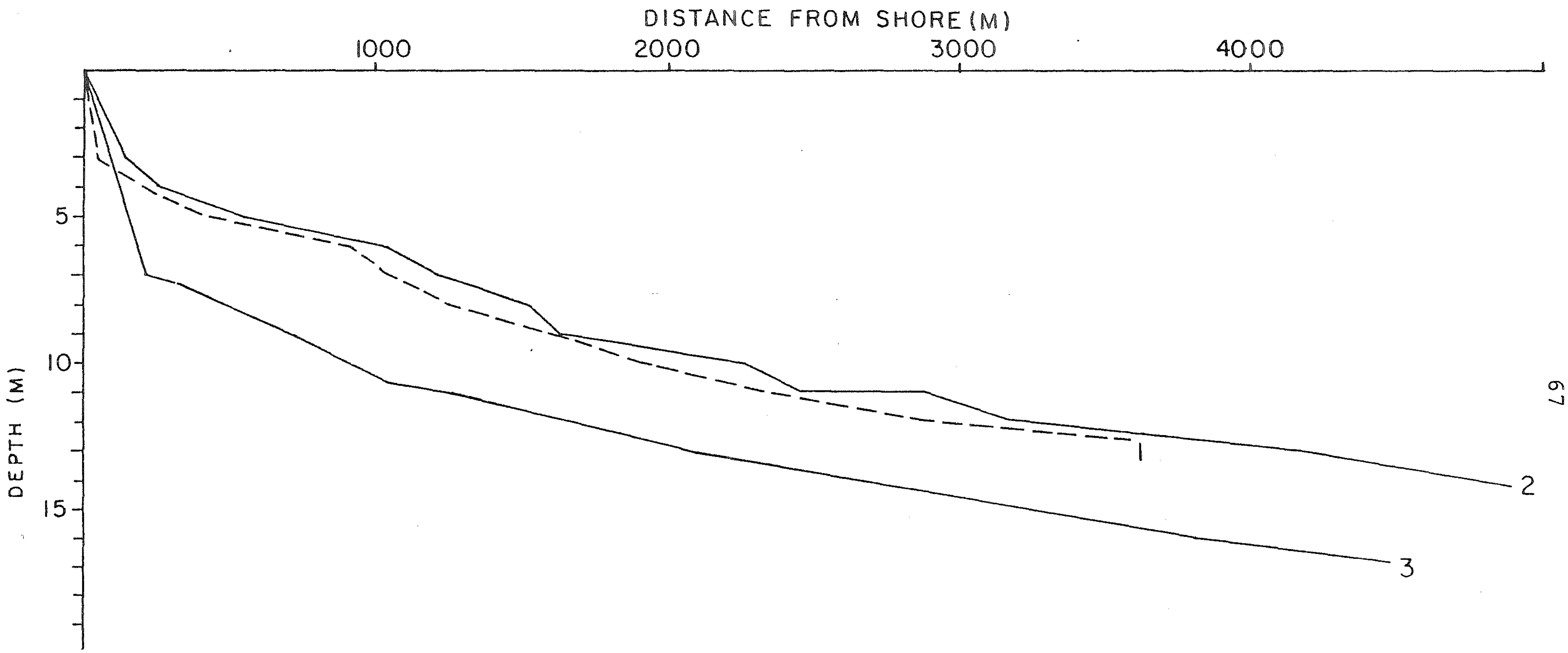


FIGURE 3.2 NEARSHORE PROFILES. THE LOCATION OF THE PROFILES IS SHOWN IN FIGURE 3.1(b).

3.3 SURFACE SEDIMENTS

3.3.1 Introduction

A sediment survey was undertaken to define the surface sediment distribution in the study area. The area had been previously surveyed by Kirk (1977) who found the seafloor to be mantled by a very uniform layer of fine and very fine sand with occasional patches of gravel or silt (see fig. 2.8).

The sediment survey was divided up into two sections. The first section involved collecting samples from the seafloor and the second section involved collecting samples on two lines in Caroline Bay, one running perpendicular to, and the other parallel to the beach.

3.3.2 Sample Collection

For the seafloor survey the majority of the 34 samples collected were obtained on four occasions. Samples were collected by the author and another diver using 0.15 m long, 0.05 m diameter, PVC tubes, which were pushed into the bottom in a scooping motion. Samples were therefore limited to the surface 0.05 m.

Once a sample was taken the tube was capped and brought back aboard the boat where the sample was transferred to a labelled plastic bag.

Sample position fixing was to have been accomplished by using a "Decca Trisponder System". The system consists of two shore based stations and a distance measuring unit (DMU) which is carried aboard the boat. The DMU gives the distance to each of the shore units and hence enables a position to be fixed with an accuracy of ± 3 m. On the first day of sample collection it was found that only one channel of the trisponder was operating. Position fixing was therefore accomplished by using the remaining trisponder channel to fix one line and by taking a line to shore to give the required position on the trisponder line. This was probably accurate to within ± 50 m. The fault in the trisponder was found to be at one of the shore stations and this was repaired before the final day of sampling and so on this occasion the trisponder alone was used for position fixing.

Samples from Caroline Bay were collected on two occasions. On the first occasion 11 samples were collected in a line running perpendicular to the beach and parallel to the North Mole. The samples were taken approximately every 70 m from the beach to the end of the North Mole. Sample location was fixed on the North Mole by pacing and samples were obtained by diving and using the short core tubes described previously. The position fixing was probably accurate to within ± 10 m. On the second occasion four samples were obtained on a line running approximately parallel to the beach, 470 m from shore. These samples were collected by a diver who, instead of using the core tubes, simply filled a plastic bag with sediment scraped from the top 0.05 m. Position fixing for these samples was made by taking a line across the Bay and another to shore and was probably only accurate to within ± 20 m.

3.3.3 Sample Analysis

All sediment samples were returned to the Physical Laboratory, Department of Geography, University of Canterbury, for analysis using standard laboratory procedures (Krumbein and Pettijohn 1938; Folk 1974). Samples were first washed to remove salt and organic matter and then air dried. Samples were found to be of four types - gravel and sand, sand only, sand and silt and silt only - and so different methods were employed for analysis.

Four of the seabed samples contained a mixture of sand and gravel. These samples were passed through seven sieves, ranging in size from 5.6 mm to 76.2 mm, by hand and the weight retained on each sieve was recorded. The remainder of the sample was then sieved at 0.5 ϕ intervals ($\phi = -\log_2$ (grain diameter mm)) by shaking the sieves for 15 minutes on an Endecott "Endrock" test sieve shaker. Again the weight retained on each sieve was recorded. The weights retained on the sieves were then converted to percentages, summed from coarsest to finest, and plotted to give a cummulative percentage frequency curve.

The remainder of the seabed samples and eight of the Caroline Bay samples contained only sands. These samples were sieved at 0.5 ϕ intervals using the sieve shaker. Again the weight retained on each sieve was recorded, expressed as a percentage, summed and plotted as a cummulative percentage frequency curve.

Two of the Caroline Bay samples contained both sand and silt. They were wet sieved to separate the two fractions and the sand was then sieved. The silt was analysed by hydrometer analysis. The remaining five Caroline Bay samples which contained silt were also analysed by hydrometer. Weight percentage for each size interval was calculated, summed and plotted as a cumulative percentage frequency curve.

Summary statistical parameters were then calculated for all samples. These included the Graphic Mean, the Inclusive Graphic Standard Deviation, and the Inclusive Graphic Skewness of Folk (1974), outlined in appendix 1. The cumulative percentage frequency curves also enabled the percentage of each sample falling into a given size interval to be read off.

3.3.4 Results

3.3.4.1 Seafloor Sediments

Sampling locations for the seafloor sediment survey are shown in figure 3.3. The reason that samples are not spaced in a regular pattern is because of the different position fixing methods outlined earlier. Figure 3.4(a) shows the surface texture for the area, divided into gravel ($\geqslant$ 4.0 mm), very fine sand (0.063 - 0.125 mm) and silt ($\leqslant$ 0.063 mm). A dominant fraction

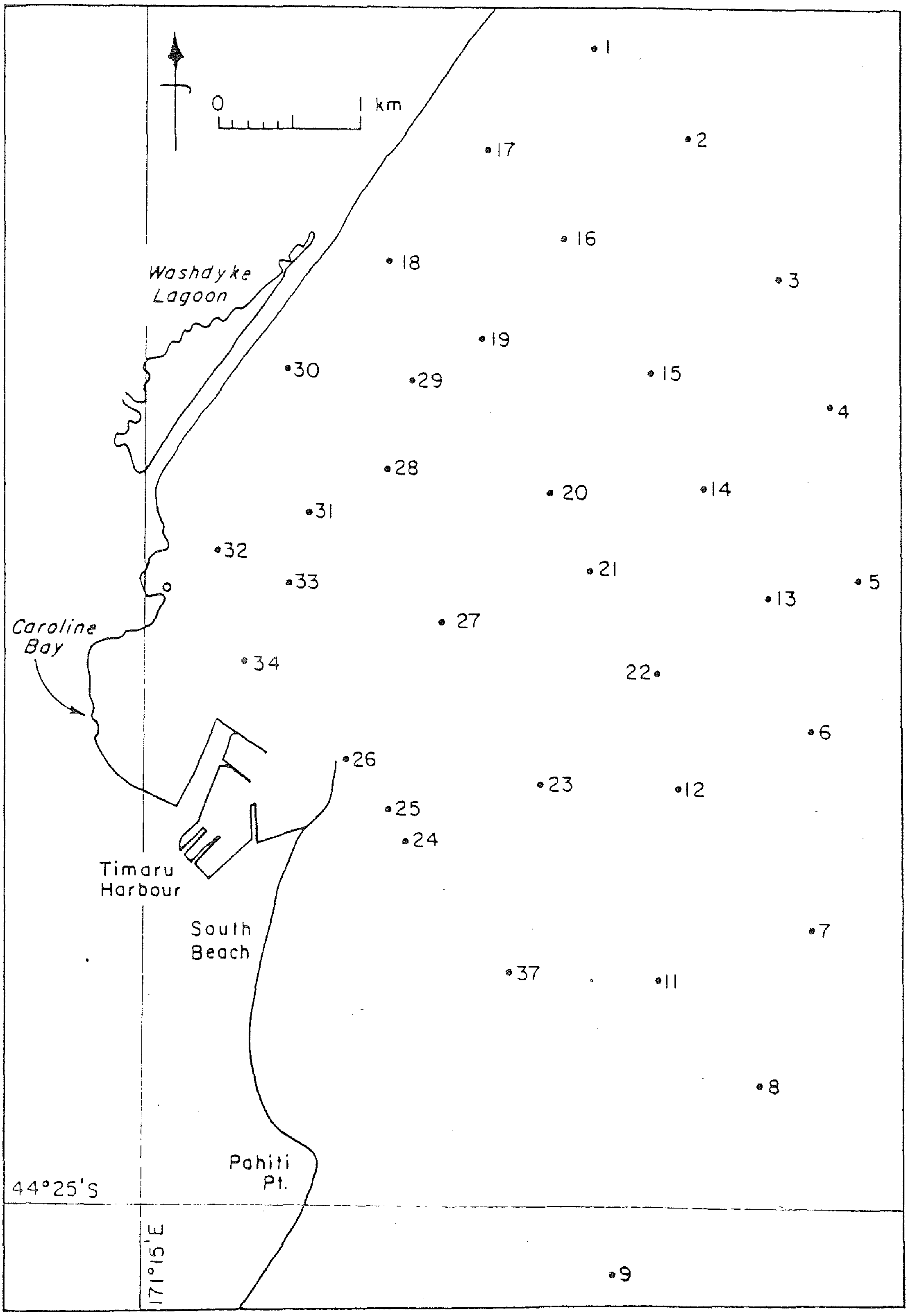


FIGURE 3.3 SAMPLE LOCATIONS FOR THE SEAFLOOR SEDIMENT SURVEY.

(a)

(b)

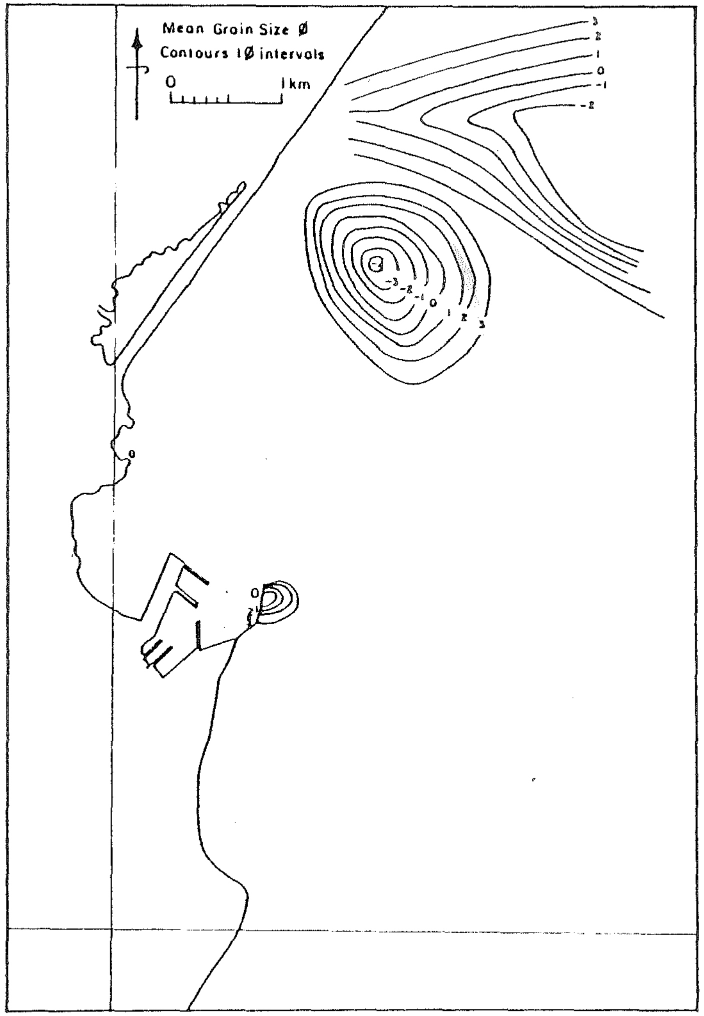


FIGURE 3.4 SEAFLOOR SEDIMENT SURVEY.

(a) SURFACE TEXTURE

(b) MEAN GRAIN SIZE

means that greater than 50% of the sample fell within that size class and a subsidiary fraction means that greater than 20% but less than 50% of the sample fell within that size class. The diagram shows that the seafloor surface texture is dominated by very fine sand. To the south of the port there is an area where silt forms a subsidiary fraction to very fine sand and to the north of the port there are two areas which contain gravel. The silt in the area to the south may be a reflection on the greater water depth there.

The Graphic Mean (mean grain size), contoured in 1 ϕ intervals, is shown in figure 3.4(b). This pattern again shows clearly the uniform nature of most of the seafloor, with patches of coarser sediment to the north and a small patch of coarse sediment on the seaward side of the Eastern Extension Breakwater.

Figure 3.5(a) shows the Inclusive Graphic Standard Deviation, which is a good measure of sorting. As could be expected, areas containing a wide range of material (that is, those with a dominant and a subsidiary fraction) are less well sorted than other areas.

Inclusive Graphic Skewness is shown in figure 3.5(b). Most samples were either near symmetrical, fine skewed or strongly fine skewed. Only three samples were skewed toward coarser sizes showing that over most of the seafloor there was an excess of fine material in the samples.

The results from this survey differ from those

(a)

(b)

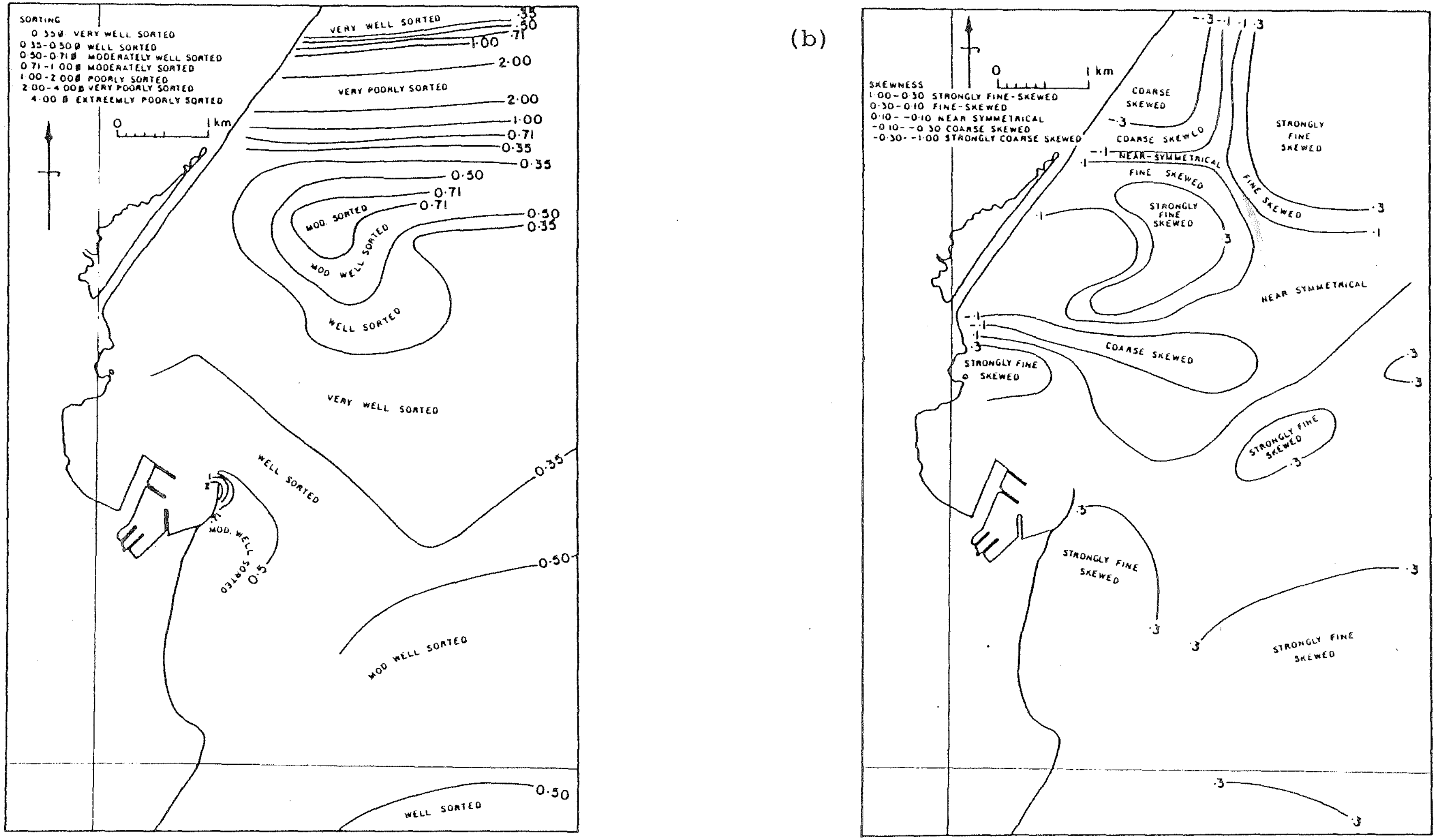


FIGURE 3.5 SEAFLOOR SEDIMENT SURVEY.

(a) SORTING

(b) SKEWNESS

of the earlier survey by Kirk (1977) in two ways. Firstly, with one exception, gravel patches appeared in different places. This may confirm the notion that the sand cover is thin and mobile and that it overlies a basement of gravel which is exposed when the sand layer is removed. The second major difference between the surveys is the grain size of the sand layer. Kirk (1977) found mean grain sizes ranging from 2.7 - 2.9 ϕ which fall into the fine sand class defined by Wentworth (1922). In the present survey the mean grain size of the sand ranged from 3.36 - 3.78 ϕ which falls into very fine sand class (most samples had very little sand outside this class). The difference between the two surveys is probably not a reflection of changes in seafloor sediment texture but is due to the different analysis techniques used. In the earlier survey the samples were analysed in a "Pelagic Electronics Model 8010 Rapid Sediment Analyser", which produces grain sizes based on the hydrodynamic settling behaviour of the sediments. Sanford and Swift (1971), in a study comparing sieving and settling techniques, found that the settling technique produced larger sizes by as much as 0.28 ϕ for fine nearshore sand and Scarlet (1979) found that the settling tube used by Kirk (1977) consistently indicated larger sizes, with this difference being as great as 0.34 ϕ.

3.3.4.2 Caroline Bay Sediments

The positions of the two lines of samples collected in Caroline Bay are shown in figure 3.6(a).

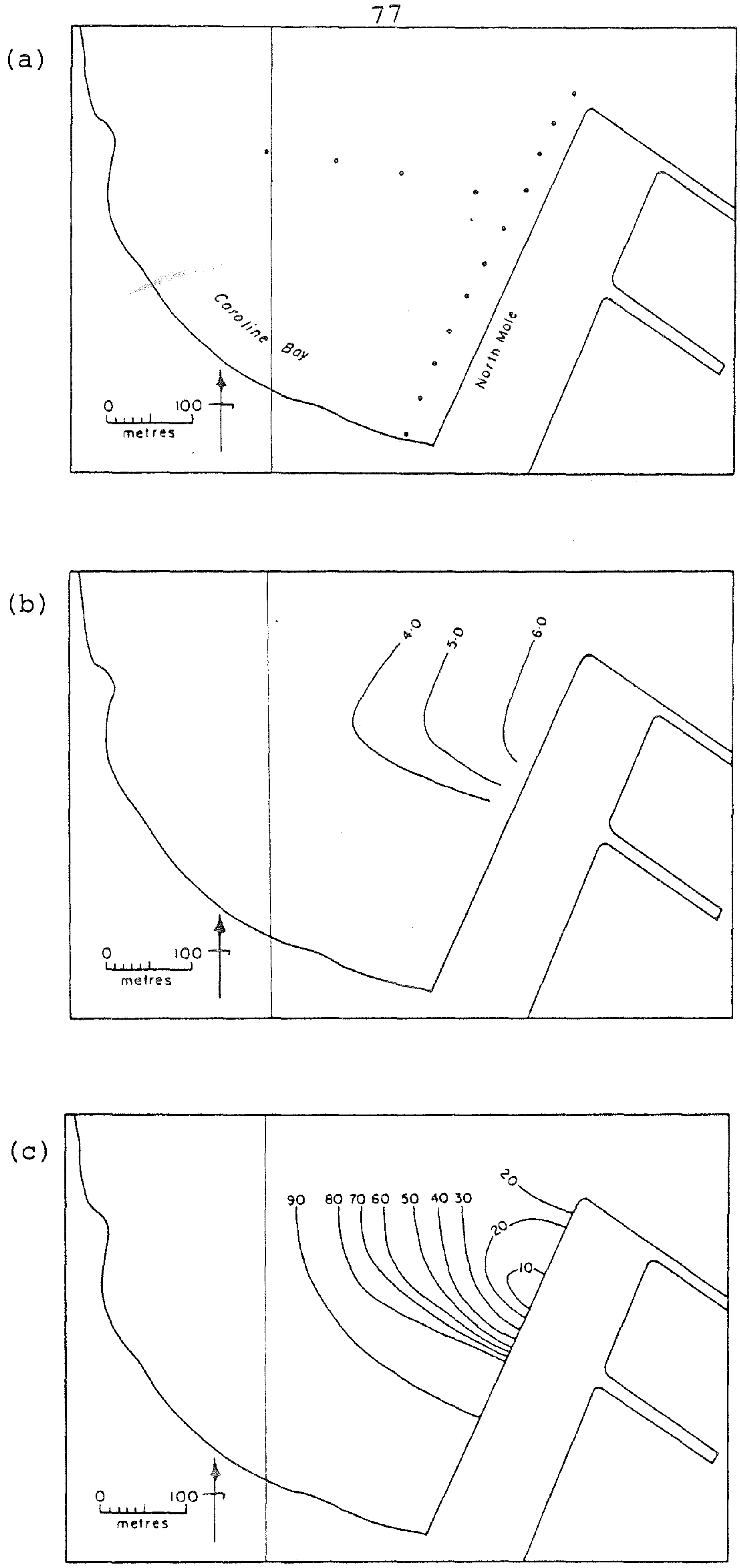


FIGURE 3.6 CAROLINE BAY SEDIMENT SURVEY.

(a) SAMPLE LOCATIONS (b) MEAN GRAIN SIZE (ϕ)

(c) PERCENTAGE OF SAND IN SAMPLE

With the exception of the line of samples running perpendicular to the beach sample coverage is very limited. However, the results from the survey do throw some light on sediment transport paths in the Bay.

The Graphic Mean (mean grain size) is shown in figure 3.6(b), contoured in 1 ϕ intervals. Two effects are apparent - firstly there is a marked seaward fining of sediment perpendicular to the beach, near the North Mole and, secondly, there is an increase in grain size across the middle of the Bay, midway down the North Mole and parallel to the beach. This pattern is repeated when the percentage of sand in each sample is plotted, as shown in figure 3.6(c).

Caroline Bay is known to be accreting at an average annual rate of 30 500 $m^3\ yr^{-1}$. From the grain size data it would appear that the sand is entering the Bay from the north and is sweeping around the Bay in an anti-clockwise direction. The area adjacent to the North Mole containing the very fine sediments is obviously sheltered by the Mole and it seems unlikely that much sand enters the Bay through this area.

3.4 HYDRAULIC CONDITIONS

3.4.1 Introduction

Bedload transport of seafloor sediment occurs in response to the current acting near the sediment/water interface. This current may be regarded as a vector sum of a series of components resulting from a series of physical effects (Pantin 1972, p. 14). Swift (1972, p. 366), however, states that velocity components are fictional though useful abstractions and that the total instantaneous shelf velocity field at a point of measurement, and the succession of these fields through time, are the only realities. Swift's point should be borne in mind throughout this section when various physical effects and current components are discussed separately.

The potential current components can be classified as coastal currents, tidal currents, density currents and meteorological currents (Swift *et al.* 1971). Meteorological currents can be further subdivided into storm surge, wave-induced oscillatory currents, longshore drift and rip currents, and direct wind currents (Swift *et al.* 1971).

The primary current component responsible for sediment transport in the study area is wave-induced and most of this section will be devoted to defining the wave field at Timaru, along with the associated currents. The roles of direct wind currents and density currents are unknown but are thought to be of much lesser importance than wave-induced oscillatory currents. Coastal currents and tidal currents are considered briefly, but again they are thought to be of lesser importance than wave-induced oscillatory currents. Because of the steeply sloping beaches in the area the surf zone is narrow and therefore longshore drift and rip currents are not important for seafloor sediment transport and are not considered here.

3.4.2 Coastal Currents

Coastal currents around New Zealand were described by Brodie (1960) from drift card data. The main flow off the east coast of the South Island is the Southland Current. The current flows north-eastwards along the Canterbury continental shelf and has been studied by Heath (1972) and Carter and Herzer (1979). Heath (1972) used data collected by Jillett (1969) seaward of the Otago Peninsula to calculate an estimated surface speed of 7 - 8 cm s^{-1}. Carter and Herzer (1979) suggest from their drift card experiments that the current has a minimum surface speed of 13 cm s^{-1}. They also used sea-bed drifters to estimate near-bottom currents and found that the highest minimum velocity was 2.5 cm s^{-1} or 20% of the surface current. This latter figure is probably the most relevant as far as seafloor sediment transport is concerned and its magnitude is such that it would have a minimal effect on sediment transport in the nearshore.

3.4.3 Tidal Currents

The tide on the Canterbury continental shelf floods to the north-east and ebbs to the south-west (Carter and Herzer 1979). The tide is semi-diurnal and has a range of 1.8 m springs and 1.2 m neaps at Timaru (Tierney 1977).

Tierney (1969) describes experiments with logships which were undertaken to define tidal currents in the vicinity of Timaru Harbour. The logships were constructed out of four steel blades 20 x 30 cm bolted at right angles to each other and attached by nylon cord to a plastic float with an attached flag. The logships were released at the entrance to the harbour during different stages of the tide and their position fixed from a boat every 30 - 45 minutes by sextant. The positions were then plotted on a plan and an estimated path for each logship was drawn.

In general it was found that an ebb tide produced a current across the harbour entrance in a south-easterly direction, and down the coast at an average of 10 cm s^{-1}. A flood tide produced the opposite results but in this case the current flowed north, with a small eddy in the lee of the Eastern Extension Breakwater.

A later section will show that the magnitudes of wave-induced currents are generally much larger than the 10 cm s^{-1} average tidal current. However, in combination with other currents, tidal currents could be responsible for sediment transport. Tidal currents are primarily long period oscillatory currents and only asymmetry between the flood and ebb tide will cause net sediment transport. Asymmetry could occur due to differences in the magnitude of the flow, the duration of the flow or a combination of both. Tierney (1969) found no difference in the magnitude of the flow so any asymmetry could only be due to the duration of the flow.

3.4.4 Waves

3.4.4.1 Wave Height And Period

Previous wave height and period data collected at Timaru has been presented by Hydraulics Research Station (1970) and in summary form by Tierney (1977). The data consists of 6 months of daily observations obtained by an echo sounder mounted aboard Timaru Harbour Board's pilot launch. Measurements were obtained at two locations, the first just off the end of the Eastern Extension Breakwater and the second 0.8 km east of the Breakwater. The launch remained stationary at each location for 5 - 10 minutes. Very little difference was found between the measurements at the two sites (Hydraulics Research Station 1970). These data, however, do not adequately describe wave conditions at Timaru. Firstly, only 6 months data were obtained, secondly, observations were only made once a day and, thirdly, an echo sounder mounted aboard a boat may not always give a true indication of wave height. The reason for this is that the motion of the boat may not always be directly related to wave height but all motion will be recorded on the echo sounder. Some interpretation is therefore necessary when analysing the records.

It was decided to collect wave height and period data during the present study and in order to improve on the quality of the existing data an "OSK 3239 Direct Wave Height Recorder, Pressure Type A" was purchased from the Ogawa Seiki Company of Japan. Figure 3.7 shows the recorder and its main components. The recorder is submersible and functions in the following way: The air in the rubber tube (1) is compressed by the water pressure at depth d such that the air pressure is balanced by the water pressure. Any change in water pressure will affect the air pressure inside the tube. As a wave passes the water pressure at depth d changes and the air in the rubber tube circulates to balance the change. The circulating air moves through the rubber hose (2) to the metal bellows (3) of the recording unit causing the bellows to expand and contract. This movement, magnified by a lever mechanism, is recorded on a paper chart (4). Recording on the carbon chart is by scratching and no ink is required. A recording of the bellows movement (that is, the pressure fluctuations) is obtained only for 10 minutes every 2 hours when a control clock switches on a motor which pulls the chart through the recording unit. The recording unit is equipped with a time marker (5) which scratches a mark on the edge of the recording paper every 20 seconds during the recording period, hence enabling paper speed to be accurately determined.

In order to eliminate pressure changes due to long period waves, such as tides, the bellows are equipped with a capillary tube or leak plug (6) which equalises the pressure on either side of the bellows. The recorder will therefore only respond to short-term (<20 s) pressure changes caused by surface gravity waves.

The metal bellows are also connected to the

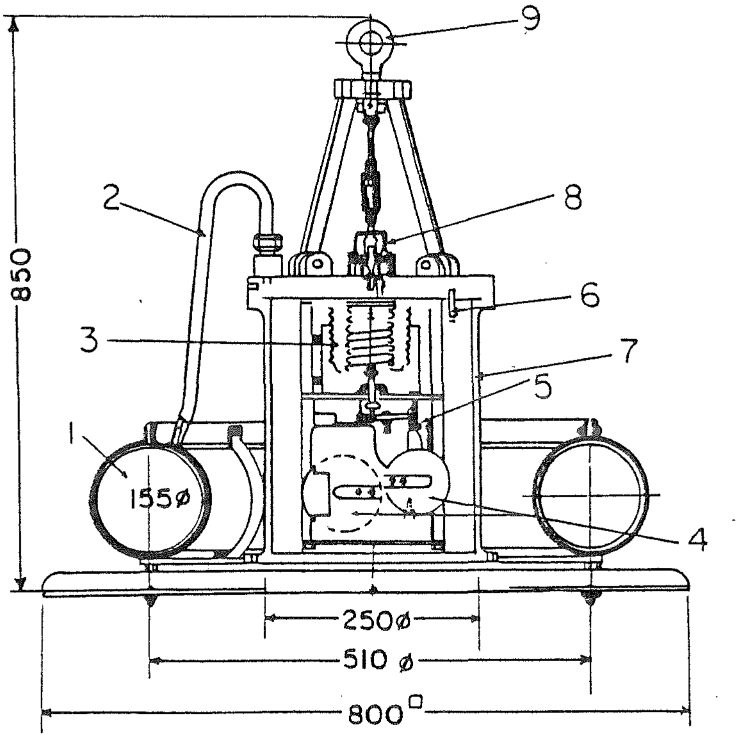


FIGURE 3.7 "OSK 3239 DIRECT WAVE HEIGHT RECORDER, PRESSURE TYPE A" USED FOR THIS STUDY. DIMENSIONS IN MM.

(1) RUBBER TUBE (2) RUBBER HOSE

(3) METAL BELLOWS (4) PAPER CHART

(5) TIME MARKER (6) LEAK PLUG

(7) WATERPROOF CASE (8) MAIN VALVE

(9) EYE BOLT

inside of the waterproof case (7) by a main valve (8) which opens automatically when the recorder is raised or lowered by the eye bolt (9). This means that air pressure on both sides of the bellows can follow changes in hydraulic pressure and always equal it at any place. Also, it protects the bellows from severe rapid expansion or contraction due to large short-term pressure changes during the raising or lowering of the recorder. When the recorder reaches its setting place the force on the eye bolt ceases and the main valve closes. Before deployment the rubber tube (1) is pressurised so that when it reaches its setting depth the tube will be approximately half inflated.

The 90 m long recording chart allows approximately 28 days of unattended recording. The batteries supplying the 6 V required for the recording paper driving motor had sufficient capacity for 2 months recording and the battery supplying the 1.5 V required by the control clock had sufficient capacity for in excess of 6 months.

The recorder was deployed from 7 October 1981 to 12 October 1982 at the location shown in figure 3.8. The recorder was moored in 12.2 m of water on the base block of a large "Sarus tower" which marked the end of Timaru Harbour entrance channel. Servicing of the recorder was planned at three weekly intervals but often it was not possible to maintain this schedule due to adverse weather or sea conditions or because of the unavailability of divers.

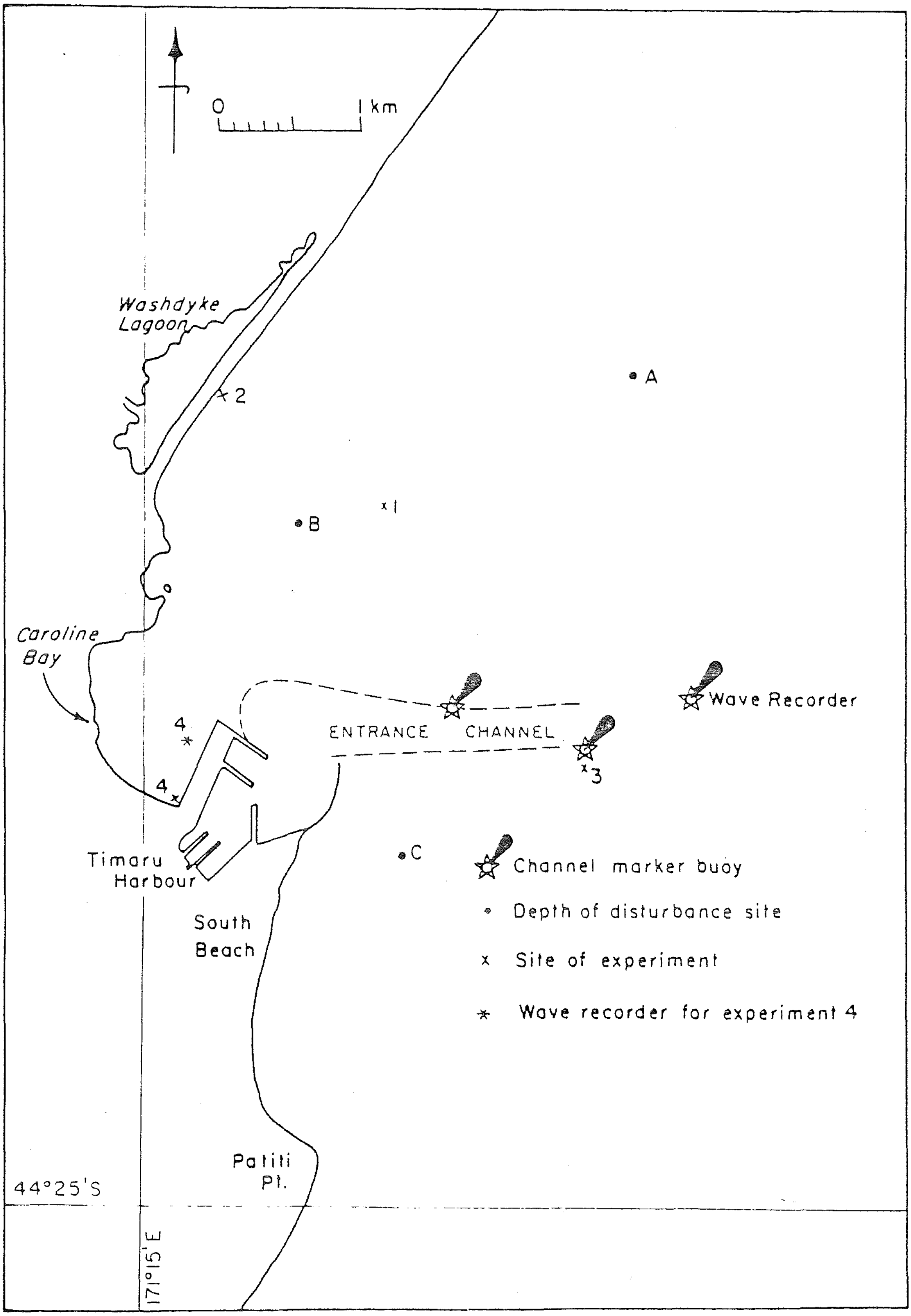


FIGURE 3.8 MAP SHOWING THE LOCATIONS OF THE WAVE RECORDER, DEPTH OF DISTURBANCE SITES, AND EXPERIMENT SITES.

During servicing the recorder was unchained from the base block by divers and raised to the surface using an air-lift. It was then lifted by winch aboard Timaru Harbour Board's pilot launch "Ohau" and returned to shore. Once back on shore the recorder was washed with fresh water, depressurised and opened. The chart was then changed and every alternative service the main batteries were also changed. The recorder was then sealed up, pressurised and returned to its mooring site.

The theory behind the operation of a pressure type wave recorder is as follows: Assume a wave with a height (H), length (L) and period (T) is running in a water depth (d). The theoretical relationship between L and T is:

$$L=gT^2\tanh(2\pi d/L) \;/\; 2\pi \qquad 3.1$$

If d and T are known it is possible to calculate L from equation 3.1. The height of a pressure wave (P), resulting from a surface wave, at a point on the bottom is obtained from the following formula:

$$P=H/\cosh(2\pi d/L) \qquad 3.2$$

Therefore when T and P are known from the data recorded on a pressure type wave recorder, L can be obtained from equation 3.1 and then, using this value, H can be obtained from equation 3.2.

The following formula was used to calculate wave height from the OSK 3239 recorder used during this study.

$$H=1.2\cosh(2\pi d/L)a \;/\; s \qquad 3.3$$

where H = surface wave height (m)

1.2 = correction factor for this type of recorder which was found to give values 20% lower than direct measurement for swell waves

d = water depth (m)

L = wavelength (m)

s = sensitivity coefficient = pen amplitude (mm)/ functional water pressure (m), which is calculated from a supplied calibration curve for the recorder (mm m^{-1})

a = amplitude of the recorded value (mm)

Equation 3.3 was checked by raising and lowering the recorder approximately 1.3 m in still water, hence simulating a wave of approximately 1.3 m amplitude. The value calculated from the recorded data was 1.2 m and so it was concluded that the recorder was functioning correctly.

Data reduction involved several steps. Firstly, the amplitude and period of the recorded waves were measured with the aid of a digitiser connected to a "Wang Model 2200S" computer in the Department of Geography, University of Canterbury. The data were recorded on disk, with identification, for each 10 minute recording interval. In the second step this information was read back into the computer, again for each 10 minute period, and real wave heights were calculated from equation 3.3. These values were ranked from smallest to largest and the summary parameters shown in table 3.2 calculated. These summary

TABLE 3.2 SUMMARY PARAMETERS CALCULATED FOR WAVE DATA.

PARAMETER		DEFINITION
H_s	:	Signficant wave height - the average height of the highest one-third waves (m).
T_s	:	Significant wave period - the average period of the highest one-third waves (s).
H_{10}	:	No name - the average height of the highest one-tenth waves (m).
T_{10}	:	No name - the average period of the highest one-tenth waves (s).
H_m	:	Mean wave height - the average height of all waves in the record (m).
T_m	:	Mean wave period - the average period of all waves in the record (s).
H_{rms}	:	Root mean square wave height - $\sqrt{1/N \sum_{i=1}^{N} H_i^2}$ (m) where N is the number of waves in the record and H_i is the height of the i th wave.
H_{max}	:	Maximum wave height - the height of the highest wave in the record (m).
H_{min}	:	Minimum wave height - the height of the smallest wave in the record (m).

parameters were stored on a separate disk along with the number of waves measured and an identification label. The original digitised data was then wiped.

For the third step the stored summary information was transferred to the University of Canterbury's "Prime 750" computer for further analysis of the summary statistics.

During its period of deployment from 7 October 1981 to 12 October 1982 the wave recorder obtained 3728 10 minute records. This was 84% of the 4439 maximum possible recording periods during this time. The 3728 recording periods contained approximately 204 000 waves with an average of 55 waves per recording period.

Figure 3.9 is a scattergram plot of H_s and T_s occurrence for the deployment period. For most of the recording periods T_s ranged from 8 - 12 s and H_s ranged from 0.4 - 1.6 m. It should be stressed at this point that the recorder only records waves which produce pressure fluctuations on the bottom and that the fluctuations are a function of wave period. To produce the same amplitude pressure change on the bottom a shorter period wave must be larger than a longer period wave and hence the recorder has greater sensitivity for long period waves. This is the reason that the scattergram only goes down to 5 s waves and that there were no instances of significant wave height less than 0.4 m combined with periods less than 8 s. The majority of occurrences of significant wave height in excess of 2.4 m occurred with wave periods from 11 - 14 s showing that in general

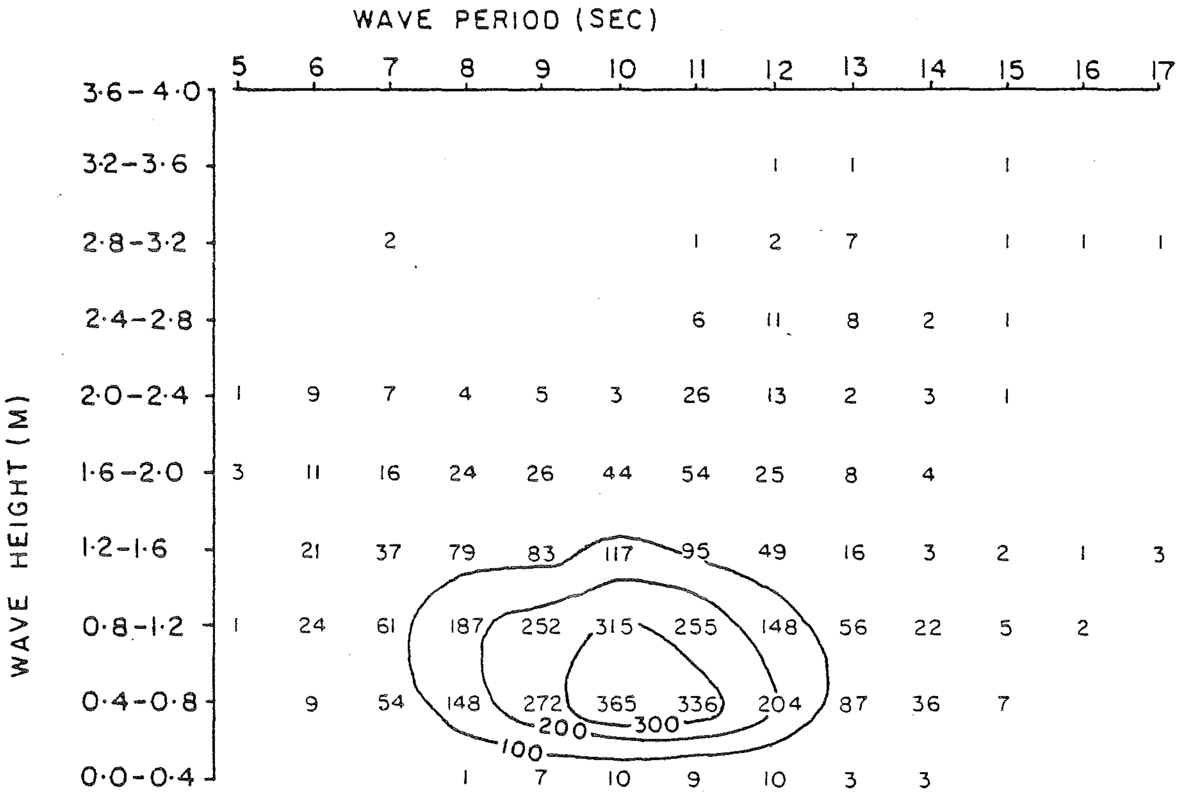


FIGURE 3.9 SCATTERGRAM PLOT OF H_s AND T_s FOR THE PERIOD 7 OCTOBER 1981 TO 12 OCTOBER 1982. VALUES AND CONTOURS REPRESENT THE NUMBER OF RECORDED OCCURRENCES.

larger wave heights were the result of long period swell waves.

Figure 3.10(a) shows the H_s percentage exceedance curve for the deployment period. H_s exceeded 0.0 m for 100% of the time and exceeded 0.4 m for 98.9% of the time. For 50% of the time H_s exceeded 0.86 m and for 3% of the time it exceeded 2.0 m.

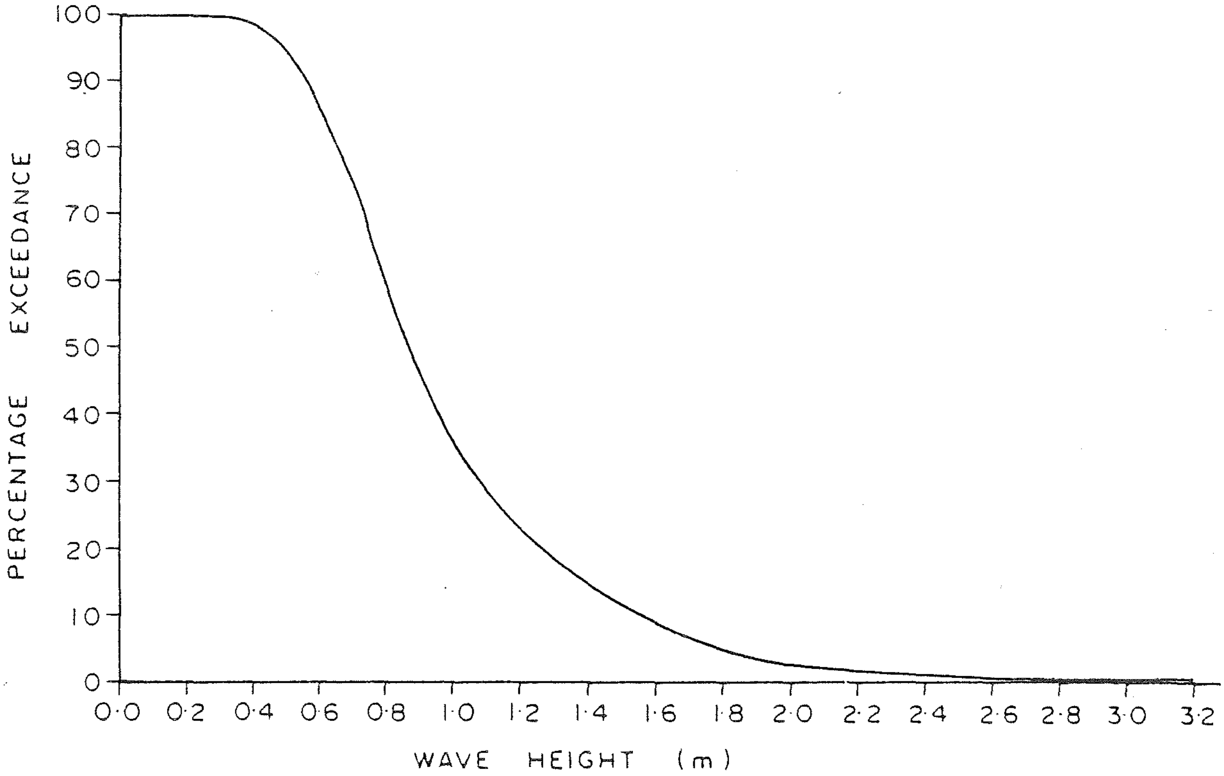
Figure 3.10(b) presents a histogram of T_s occurrence for the deployment period. The graph is symmetric and uni-modal. Periods range from 5 - 17 s with the modal value falling at 10 s, which occurs 22.9% of the time. T_s ranges from 8 - 12 s for 85.4% of the time.

Table 3.3 contains the average wave statistics for the 3728 recording periods along with the standard deviation, maximum, and minimum values for each statistic. Mean significant wave height $\overline{H}_s$ was 0.97 m and mean significant wave period $\overline{T}_s$ was 10 s.

Regression analysis was used to test the relationship between H_s and H_{10}, H_s and H_m, H_s and H_{rms}, H_s and H_{max}, and H_s and H_{min}. The results are shown in table 3.4. H_s is very highly correlated with H_{10}, H_m and H_{rms}. It is highly correlated with H_{max} but poorly correlated with H_{min}. With the exception of H_{min} it is therefore possible to calculate any of the wave height statistics from H_s. For this reason wave height exceedance curves are presented for H_s only.

The relationships between H_s and the other wave statistics can also be expressed in ratio form. The ratios

(a)



(b)

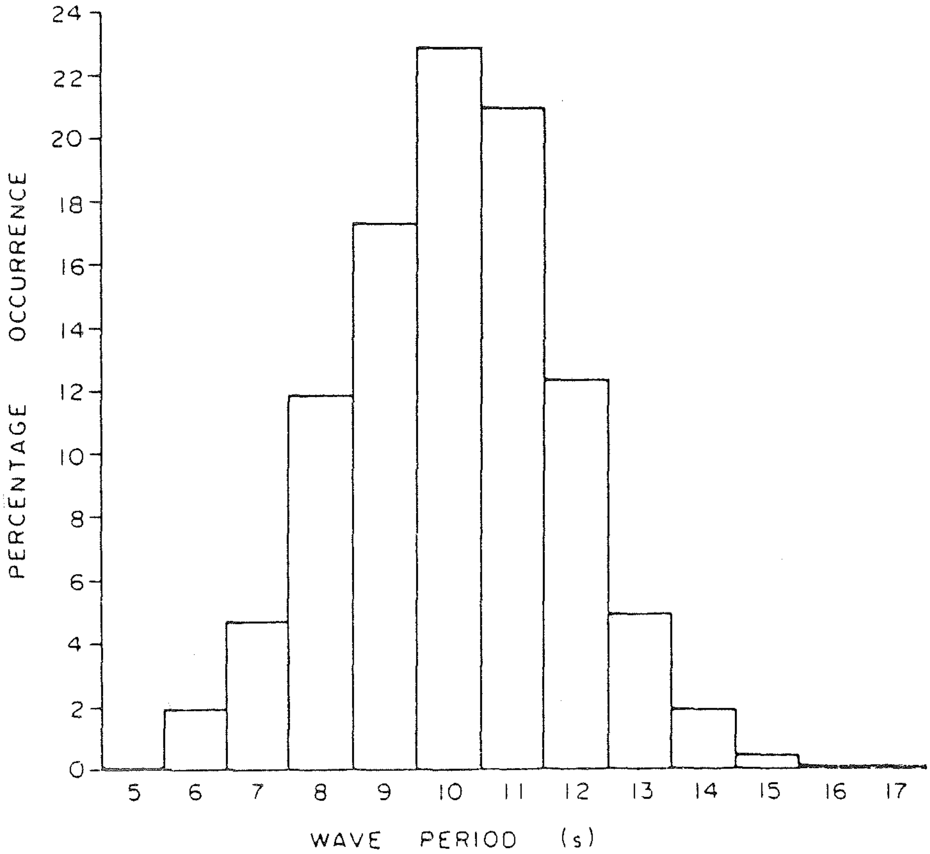


FIGURE 3.10

(a) H_s PERCENTAGE EXCEEDANCE AND (b) T_s PERCENTAGE OCCURRENCE

FOR THE PERIOD 7 OCTOBER 1981 TO 12 OCTOBER 1982.

TABLE 3.3 AVERAGE WAVE STATISTICS FOR THE PERIOD 7 OCTOBER 1981 TO 12 OCTOBER 1982.

PARAMETER	MEAN	STANDARD DEVIATION	MAXIMUM	MINIMUM
H_s (m)	0.97	0.44	3.33	0.32
T_s (s)	10	1.76	17	5
H_{10} (m)	1.23	0.56	4.28	0.37
T_{10} (s)	9	2.08	17	4
H_m (m)	0.64	0.29	2.33	0.22
T_m (s)	11	1.54	17	7
H_{rms} (m)	0.71	0.32	2.51	0.24
H_{max} (m)	1.55	0.76	6.30	0.41
H_{min} (m)	0.12	0.12	0.79	0.00

TABLE 3.4 CORRELATIONS BETWEEN SIGNIFICANT WAVE HEIGHT AND OTHER WAVE STATISTICS MEASURED DURING THIS STUDY.

VARIABLE 1	VARIABLE 2	r	r^2	SIGNIFICANCE	INTERCEPT	SLOPE
H_s	H_{10}	0.98	0.97	0.01	0.03	0.76
H_s	H_m	0.99	0.98	0.01	0.00	1.51
H_s	H_{rms}	0.99	0.99	0.01	0.00	1.38
H_s	H_{max}	0.88	0.79	0.01	0.18	0.51
H_s	H_{min}	0.59	0.35	0.01	0.73	2.09

for this study, excluding H_{min}, are presented in table 3.5 along with theoretical values derived by Longuet-Higgins (1952) and recorded data from Wiegel (1949), Putz (1952) and Goodknight and Russell (1963). The values obtained during this study compare favourably with both the theoretical values and the values obtained from other recorded data.

TABLE 3.5 RELATIONSHIP BETWEEN SIGNIFICANT WAVE HEIGHT AND OTHER WAVE STATISTICS.

DESCRIPTION	H_m/H_s	H_{rms}/H_s	H_{10}/H_s	H_{max}/H_s
Theoretical prediction by Longuet-Higgins (1952) for a narrow spectrum	0.64	0.71	1.27	1.53-1.85[1]
Recorded Data from Wiegel (1949)	-	-	1.29	1.87
Recorded Data from Putz (1952)	0.62	-	1.29	-
Recorded Data from Goodknight and Russell (1963)	0.60	0.69	1.25	1.57
This study - 3728 observations	0.62	0.70	1.22	1.56

[1] This value varies with the wave period and the length of the record.

The wave data can be presented on a monthly basis. Table 3.6 shows for each month the number of recording periods, the maximum possible number of recording periods, and the percentage of the maximum that was recorded. The low percentage recorded during January was due to a shortage of divers during the summer holiday period and the low percentages during May and June arose because the recorder was being repaired. Data are not presented for October 1982 because the recorder was deployed for only 12 days and obtained only 37% of the maximum possible recording periods.

TABLE 3.6 NUMBER OF WAVE RECORDING PERIODS PER MONTH.

MONTH		NUMBER OF RECORDING PERIODS	MAXIMUM POSSIBLE	% OF MAXIMUM RECORDED
October	1981	292	372 (294)[1]	78.5 (99.3)[1]
November		343	360	95.3
December		371	372	99.7
January	1982	228	372	61.3
February		336	336	100.0
March		368	372	98.9
April		326	360	90.6
May		203	372	54.6
June		233	360	64.7
July		304	372	81.7
August		331	372	89.0
September		256	360	71.1
October		137	372 (137)[2]	36.8 (100.0)[2]

[1] The numbers in brackets are the maximum possible recording periods and the percentage of maximum recorded for the period 7 October to 31 October 1981 during which the recorder was deployed. The unbracketed figures represent the period 1 October to 31 October 1981.

[2] The numbers in brackets are the maximum possible recording periods and the percentage of maximum recorded for the period 1 October to 12 October 1982 during which the recorder was deployed. The unbracketed figures represent the period 1 October to 31 October 1982.

Figure 3.11 presents H_s exceedance curves for each month. A comparison of the curves reveals that with the exception of June all curves are fairly similar with the length of the tail being the main difference. June clearly stands out as a month with much greater wave heights. H_s in June dropped below 0.4 m for only 2% of the time and exceeded 1.8 m for 20% of the time. This may in part be due to the fact that recordings were obtained for only 65% of the month.

Percentage occurrence graphs for T_s are presented in figure 3.12. All months have graphs that are roughly symmetrical and all except May are uni-modal. May is weakly bi-modal with one mode occurring at 8 s and another at 10 - 11 s.

Mean H_s and T_s statistics are presented for each month in table 3.7. April, May, June and July all had mean H_s values greater than the average for the full set of data. October, December and January had the lowest mean H_s values. Mean T_s was fairly consistent for each month ranging from 9 - 11 s.

3.4.4.2 Oscillatory Currents Beneath Waves

Several attempts were made to measure wave-induced horizontal oscillatory currents near the seabed using a specially designed current meter. The meter was designed and built in the Geography Department, University of Canterbury, and had previously been used by Gillie (1979) to measure a profile of horizontal oscillatory

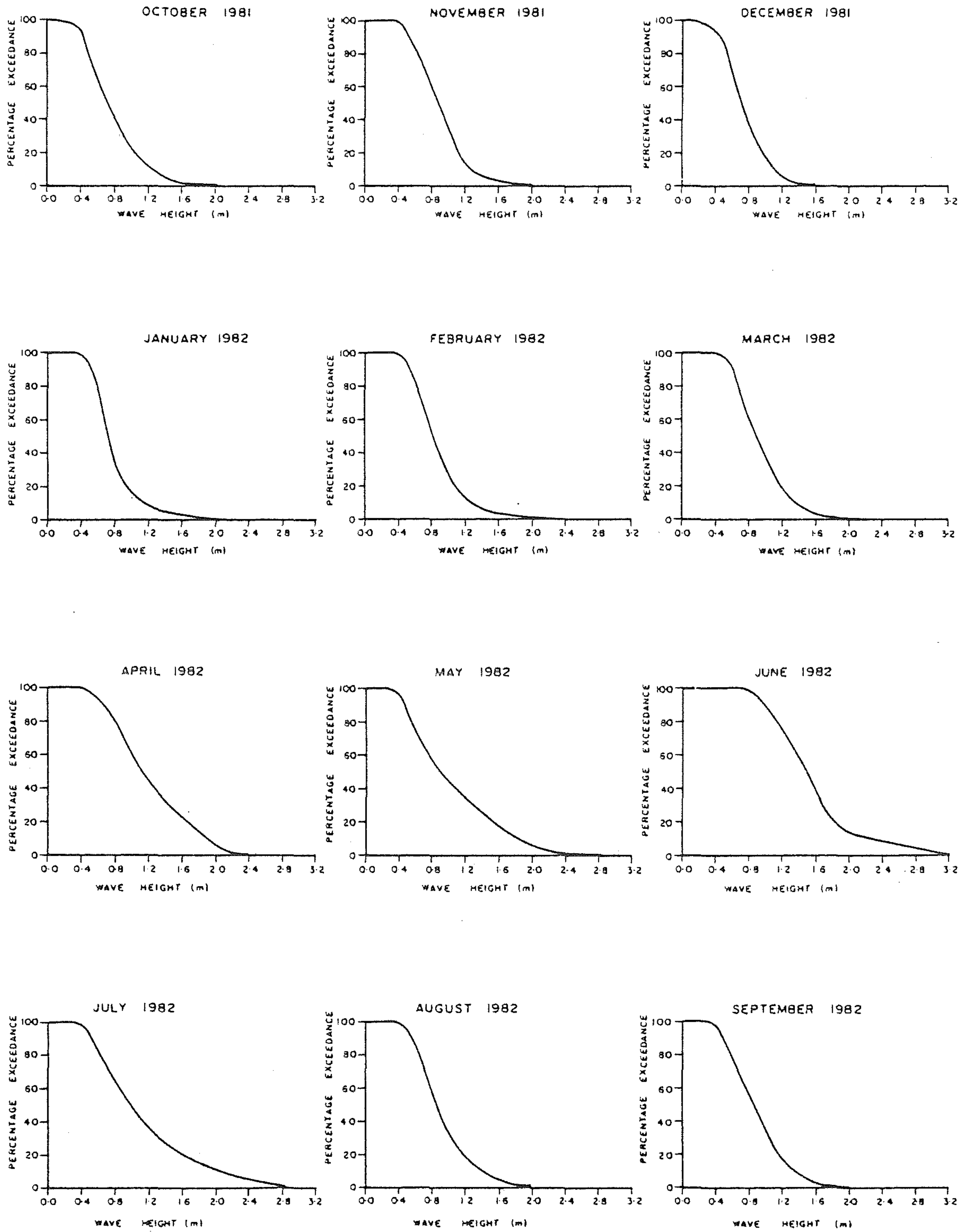


FIGURE 3.11 H_s PERCENTAGE EXCEEDANCE FOR EACH MONTH FROM OCTOBER 1981 TO SEPTEMBER 1982.

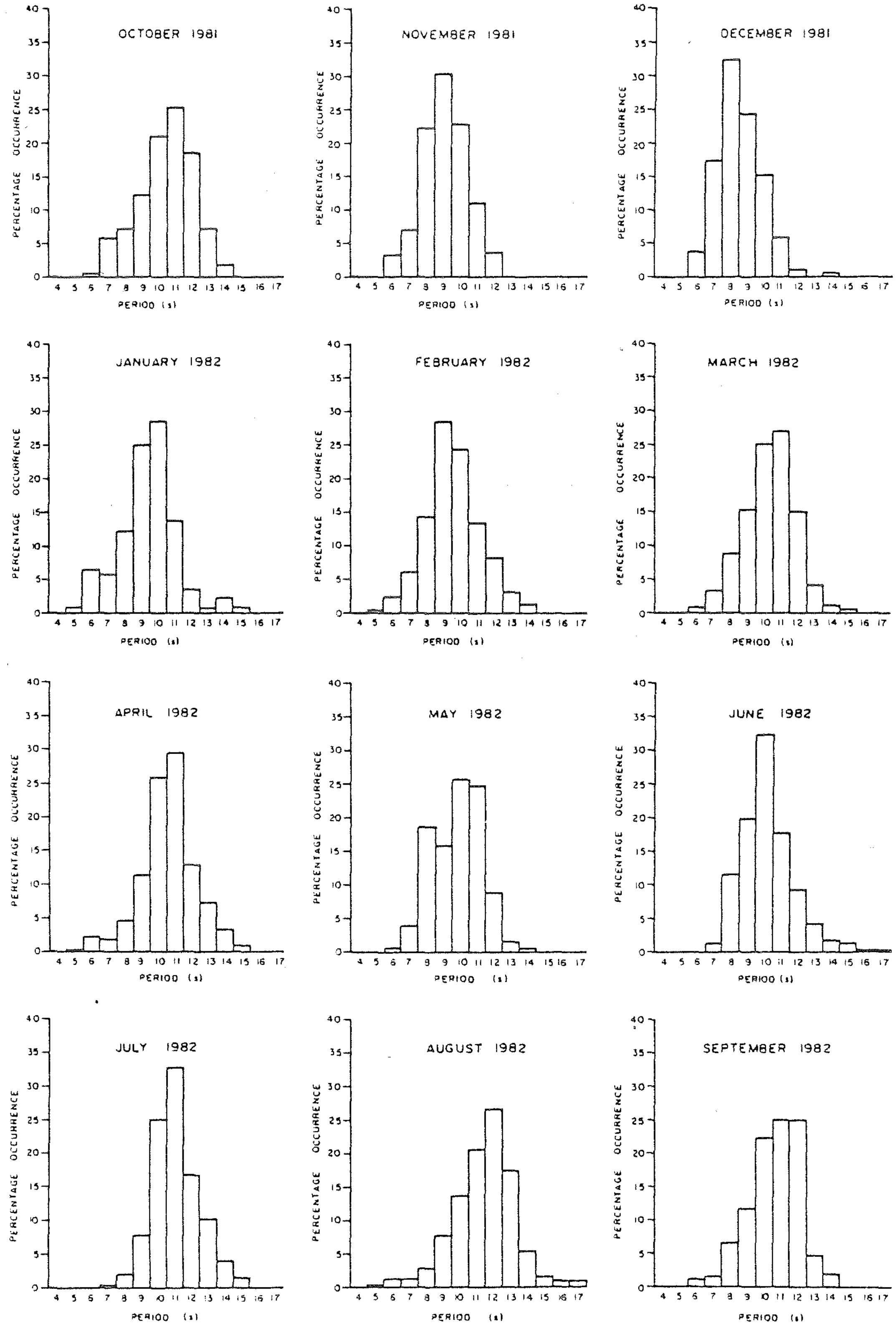


FIGURE 3.12 T_s PERCENTAGE OCCURRENCE FOR EACH MONTH FROM OCTOBER 1981 TO SEPTEMBER 1982.

TABLE 3.7 MEAN SIGNIFICANT WAVE HEIGHT AND PERIOD OCTOBER 1981 TO SEPTEMBER 1982.

a) H_s (m)

MONTH		MEAN	STANDARD DEVIATION	MAXIMUM	MINIMUM
October	1981	0.78	0.33	2.34	0.32
November		0.91	0.30	2.26	0.43
December		0.75	0.25	1.48	0.33
January	1982	0.74	0.31	2.28	0.40
February		0.87	0.29	2.08	0.45
March		0.94	0.30	2.50	0.47
April		1.20	0.48	2.37	0.45
May		1.02	0.55	3.05	0.35
June		1.55	0.52	3.33	0.74
July		1.17	0.63	3.12	0.49
August		0.94	0.33	2.37	0.50
September		0.89	0.29	2.19	0.38

b) T_s (s)

MONTH		MEAN	STANDARD DEVIATION	MAXIMUM	MINIMUM
October	1981	10	1.69	14	6
November		9	1.33	12	6
December		9	1.33	14	6
January	1982	9	1.76	15	5
February		10	1.59	14	5
March		10	1.51	15	6
April		11	1.67	15	5
May		10	1.46	14	6
June		10	1.63	17	7
July		11	1.39	15	7
August		11	1.83	17	5
September		11	1.52	14	6

velocities close to a bed of wave-formed dunes at 18 m depth. The meter is similar in design and construction to those built by Morrison (1968) to measure wind turbulence and Smith and Harrison (1970) to measure tidal currents.

The meter consists of up to three sensors mounted on a tripod. Each sensor consists of a lightweight plastic sphere connected by a thin rod to the free end of a flexible metal beam. The beam has two strain gauges glued to each side and these are wired in a bridge circuit. As a current flows the sphere is deflected in proportion to the current velocity. This deflection of the sphere causes a proportional flexing of the metal beam which in turn causes an imbalance in the bridge circuit. As a result there is a small voltage output which has a magnitude proportional to the current velocity. The sensors are bi-directional and are able to respond rapidly to a current which has a 180° direction change every half wave period. Conventional current meters are either unable to orient themselves fast enough or, if they are omni-directional, will not differentiate between the crest and the trough velocity. With the meter used for this study a 180° direction change would be recorded by a change in the sign of the voltage output.

The only change in design of the meter for the present study was the addition of a copper pipe shield around the metal beam so that currents only acted on the drag sphere and thin connecting rod, and not on the metal beam itself.

Previous calibration of the current meter by Gillie (1979) was achieved by applying a static force to each sensor and recording the resulting voltage output. For the present study the sensors were calibrated dynamically in a rating tank. The rating tank is located at the Ministry of Works and Development, Water and Soil Instrument Service Centre, Kaianga, and is the only one of its kind in New Zealand. The tank, 50.3 m long, 2.0 m wide and 1.8 m deep, is straddled by an electrically driven carriage which tows current meters at specific velocities. In the present case each sensor was towed both forwards and backwards at 10 cm s^{-1} incremental velocities from 10 cm s^{-1} up to 100 cm s^{-1}. The voltage output was recorded and calibration curves were plotted for all sensors. As an example, the calibration curves for two sensors are shown in figure 3.13. In general all curves were of the same form and there was little difference between forward and backward motion.

When operating the recorder the tripod was lowered to the bottom and stabilised by driving pins into the seabed. A diver (the author) then aligned the sensors parallel to the wave-induced currents. This proved to be a difficult task because the current direction, as felt by the diver, could be quite variable with each successive wave. Once the sensors were aligned their orientation was determined by compass so that it would be possible later to distinguish between crest and trough velocities. A 20 m long plastic tube enclosed the wires carrying the 5 V regulated input to the sensors and the output signals

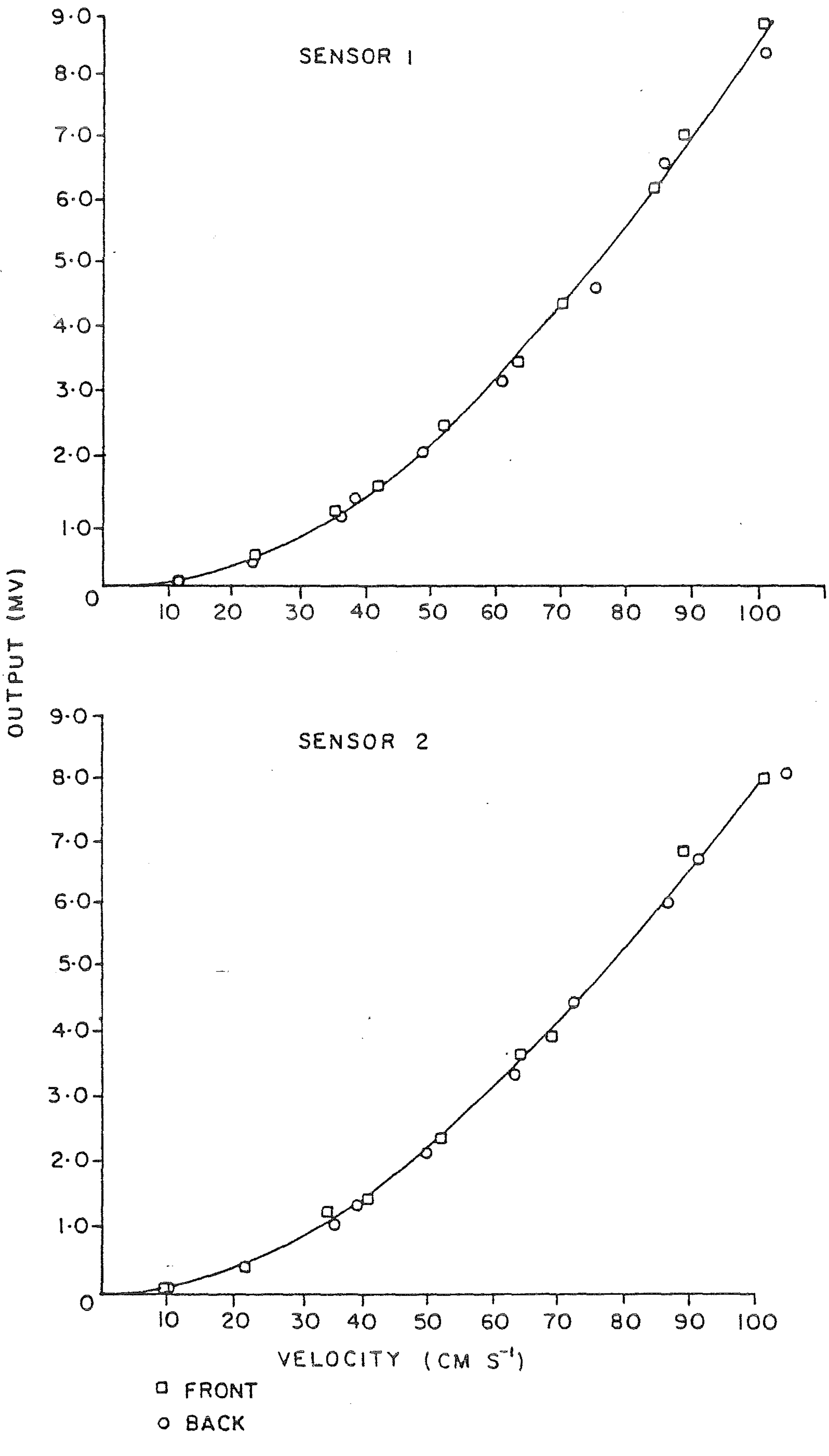


FIGURE 3.13 CURRENT METER CALIBRATION CURVES FOR SENSOR 1 AND SENSOR 2.

from the sensors to a recorder aboard an anchored boat. The recorder had only a single channel so that only one sensor could be recorded at a time. A small switch box enabled the required sensor to be selected.

It is important to realise that while the primary intention was to measure the wave-induced horizontal oscillatory currents the current meter would sense any current or current-component acting perpendicular to the sensor and no differentiation of the currents would be possible.

During the summer of 1981 the current meter was operated in the study area. However, it was continually plagued with sensor failure and only five successful recordings were obtained. During the winter of 1981 the meter was completely rebuilt with new electrical components and wiring and the sensors were re-calibrated in the rating tank. Despite this effort the meter was again plagued with failure during November 1981 and only two successful recordings were obtained before attempts to use the meter were discontinued.

Nearly all of the seven successful recordings had a zero drift problem which meant that the zero line had to be drawn in by eye. Drawing of the zero line requires some knowledge about its expected position and hence makes it impossible to examine asymmetry in the crest and trough currents without bias. One of the first records showed no drift of the zero line but for this record it was not known which currents were under troughs and which were under crests, and failure of the sensor being used during the operating period made this impossible to ascertain later.

Gillie (1979) also experienced problems with zero drift, most of which occurred immediately after placing the meter on the seabed. This problem and the high failure rate of sensors are thought to be due to inadequate waterproofing of the electrical components on the sensors and considerable improvement would be necessary before any future use of the meter.

During the first five successful recordings an echo sounder was operated simultaneously on board the boat to give an indication of the waves during the recording period. As mentioned previously, such records can be difficult to interpret because of boat movements not directly related to waves. This was particularly so in most of these cases because the echo sounder transducer was mounted on the side of the boat and therefore was sensitive to sideways motions of the boat as well as forward-backward motions. During the final two recordings an estimate of the wave height could only be obtained from the wave recorder which was moored some distance from the current meter site.

All echo sounder charts and current records were analysed by digitiser using a modified version of the program used to analyse the wave charts. Values of H_s and T_s were obtained from the wave records, the final two estimates coming from the wave recorder records. For the current U_s was calculated, being defined as the average of the highest one-third current velocities (which were averaged for crest and trough).

Theoretical wave-induced horizontal oscillatory currents were calculated from linear (Airy) wave theory using the recorded wave information. The equation used is presented in appendix 2. Strictly, the theory applicable at the sites is Stokes' second order wave theory (U.S. Coastal Engineering Research Center 1977, fig. 2-7, p. 2-35). When trough and crest velocities are averaged, however, both theories produce the same results.

Table 3.8 presents the recorded wave and current data along with the calculated current and the water depth at the measurement site. In all but one case the calculated current exceeded the measured current. Possible reasons for these differences include inadequate wave data, incorrect alignment of the current sensors and wave theory limitations. The measured and calculated values were used in a regression analysis, with the measured current as the independent variable. The results from this regression are shown in table 3.9. The regression was significant at the 1% level and explained 71% of the variance in the data. If a greater number of measurements had been obtained the regression equation could have been used to correct any calculated values made from wave data. As it stands, however, it is not possible to have confidence in the equation and therefore any calculated currents can be considered as estimates which are probably too high.

TABLE 3.8 WAVE CONDITIONS, WATER DEPTH, AND MEASURED AND CALCULATED HORIZONTAL OSCILLATORY WAVE-INDUCED CURRENTS.

DATE	H_s (m)	T_s (s)	WATER DEPTH (m)	MEASURED U_s (cm s^{-1})	CALCULATED U_s (cm s^{-1})
07/01/81	0.91	7	11.5	18	28
14/01/81	0.74	9	7.0	28	38
21/01/81	1.09	9	9.5	32	47
22/01/81	0.80	9	6.5	36	44
10/02/81	0.65	8	7.0	23	32
10/11/81	0.60	9	7.6	32	30
12/11/81	1.08	11	7.6	42	56

TABLE 3.9 REGRESSION ANALYSIS RESULTS FOR U_s MEASURED VERSUS U_s CALCULATED.

r	r^2	SIGNIFICANCE	INTERCEPT (A)	SLOPE (B)
0.834	0.710	0.01	4.259	0.659

3.4.4.3 Wave Direction

A wave direction frequency diagram for Timaru is presented by Hydraulics Research Station (1970) and by Tierney (1977). The diagram, reproduced here in figure 3.14(a), is based on 496 daily onshore observations. The diagram shows the predominant wave direction to be from the sector between east and south-east. Waves arrived from this sector for nearly 85% of the time (Hydraulics Research

(a)

(b)

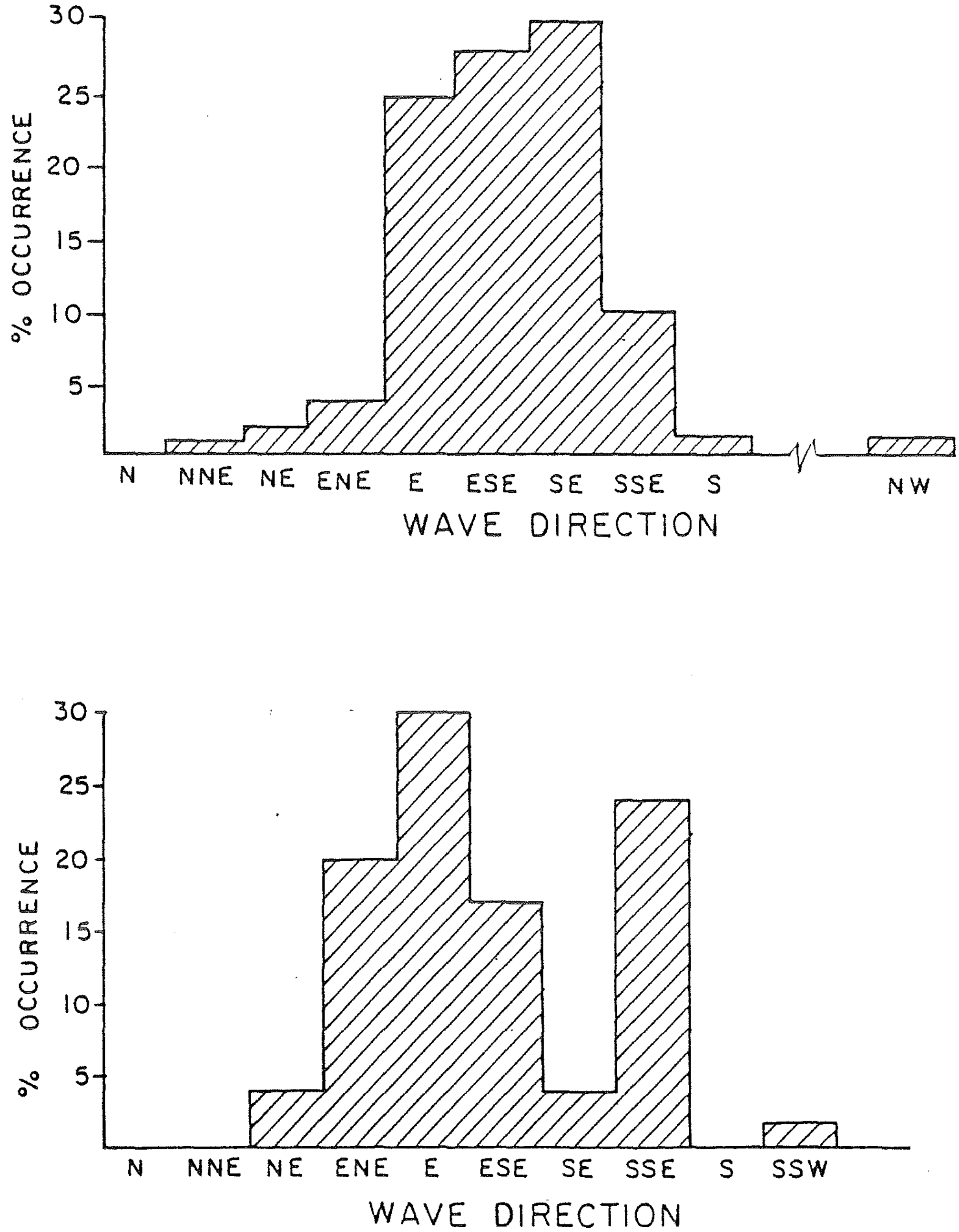


FIGURE 3.14 TIMARU WAVE DIRECTION.

(a) FROM HYDRAULICS RESEARCH STATION (1970) AND TIERNEY (1977). N = 496.

(b) OFFSHORE DATA COLLECTED DURING THIS STUDY. N = 53.

Station 1970)

A limited number of offshore wave direction observations were obtained during the present study at the site where the wave recorder was deployed (see fig. 3.8). During the period February to May 1982 53 observations were made and these were used to construct the wave direction frequency diagram shown in figure 3.14(b). During the observation period waves from the east dominated followed by waves from the south-south-east. The greater spread of dominant wave directions at this site compared to the shore based observations may be due to the fact that the waves are less refracted at this point offshore. However, it may also be simply a function of the limited number of observations made. Sending a boat out to observe wave direction at a point offshore is very costly and this is the reason why the number of observations obtained during this study was limited.

3.4.4.4 Wave Refraction

According to linear wave theory wave phase velocity depends on water depth (d) and wavelength (L). The relative importance of water depth and wavelength depends on the ratio d/L. When this ratio is greater than 1/2 the velocity is solely dependant on wavelength. As the ratio decreases water depth becomes increasingly more important and when the ratio reaches about 1/25 velocity becomes solely dependant on water depth (Wiegel 1964).

When travelling in water depths such that $d/L < 1/2$ each part of a wave travels with a phase velocity that is dependant on water depth, whether or not the wave is linear (Wiegel 1964). Therefore if a wave is travelling at an angle to the bottom contours different parts of the wave will be in different water depths and hence will travel at different velocities. This will cause the wave to bend or refract and there will be a tendency for the wave crests to parallel the depth contours (Inman 1963). Wave rays or orthogonals are lines running perpendicular to the wave crests. They will tend to turn into shallow water as the crests tend to parallel the depth contours (Inman 1963).

A computer program, described in Wilson (1966), was used to produce wave refraction diagrams for the predominant sector of wave directions at Timaru. The analysis covered that area shown on the "Approaches to Timaru" section of New Zealand Hydrographic Chart No. 6422. This chart and the fair sheet containing the original soundings provided the bathymetric information required as inputs for the program. Output from the program consisted of plotted diagrams of the wave rays and did not include the wave crests.

Refraction diagrams for 10 s period waves from the east, east-south-east and south-east are shown in figure 3.15. The shoreline in these diagrams was drawn in by hand. It should be noted that the wave refraction analysis should have begun in deep water ($d > L/2$) and should have used wave direction data recorded at this offshore location. However, insufficient bathymetric data

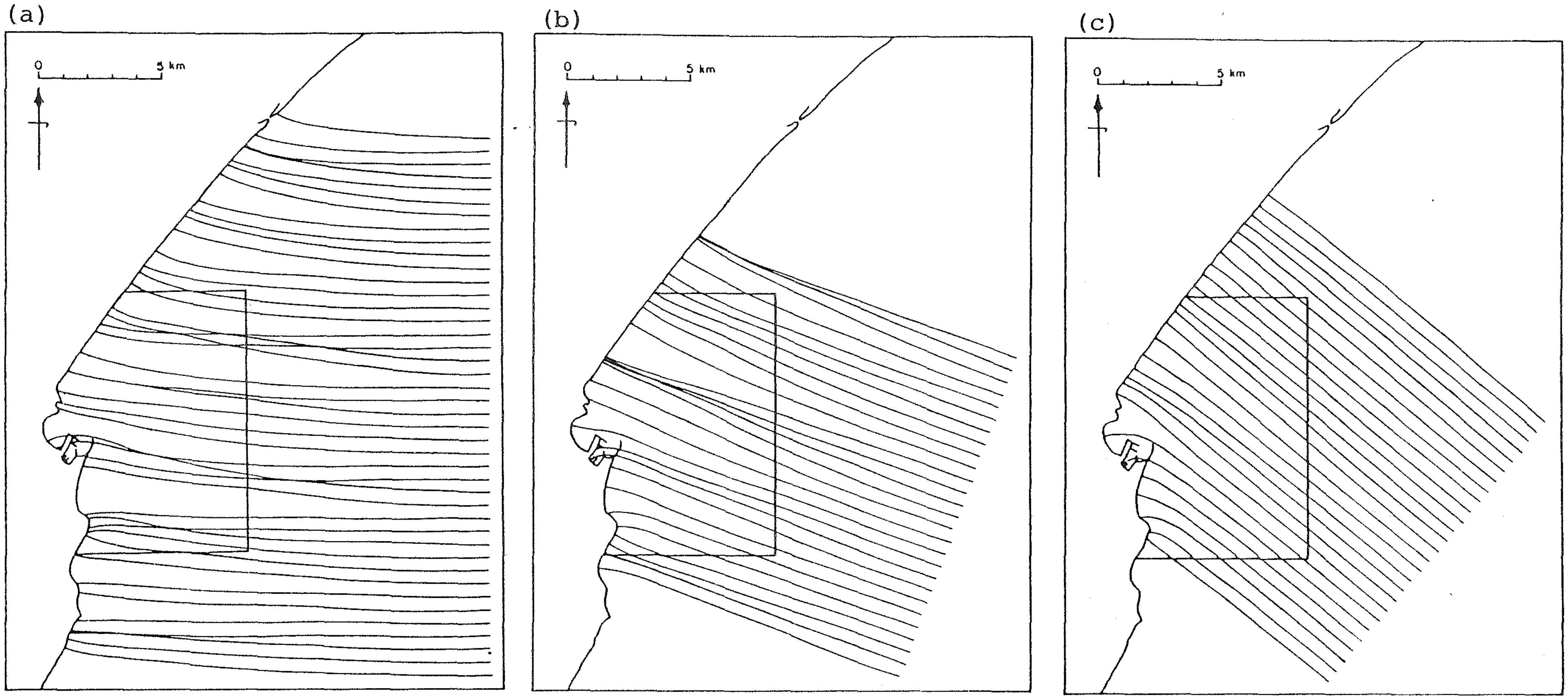


FIGURE 3.15 WAVE REFRACTION DIAGRAMS. THE BOUNDARY OF THE STUDY AREA IS SHOWN ON EACH DIAGRAM.

(a) EASTERLY WAVES (b) EAST-SOUTH-EAST WAVES (c) SOUTH-EAST WAVES and a lack of wave direction data for the offshore area made this task impossible and limited analysis to its present form.

In general, waves from the south-east are the least refracted because the initial crests closely parallel the bottom contours. Waves from the east make the greatest angle with the bottom contours and therefore undergo the greatest amount of refraction.

In wave refraction analysis it is usual to assume that the wave energy between orthogonals remains constant (U.S. Coastal Engineering Research Center 1977, p. 2-66). However, when there are points where orthogonals cross, as for example in figure 3.15(a), analysis of wave behaviour is not possible (U.S. Coastal Engineering Research Center 1977, p. 2-78). In general, areas where wave orthogonals are concentrated are high energy areas and areas where wave orthogonals are divergent are low energy areas.

Figure 3.15(a) for easterly waves shows a semi-regular pattern of convergence and divergence along the coast but in several places crossed orthogonals make interpretation difficult. Within the study area itself there are convergences of energy at Patiti Point, Dashing Rocks and Washdyke. To the north of the port it would appear that waves are tending to travel in an east-south-east direction.

Figure 3.15(b) for east-south-east waves again shows a convergence of energy at Patiti Point, with two other strong convergence points occurring to the north of the port. Waves tend to retain their east-south-east orientation until very close to the shore.

Figure 3.15(c) for south-east waves again shows very little refraction until very close to shore. To the north of the port most orthogonals simply run perpendicular to the shore while to the south they bend so that again the orthogonals approach perpendicular to the shore.

3.5 DEPTH OF DISTURBANCE

Rods driven into the seabed can be used to measure vertical changes in seabed elevation and the depth to which sediment is disturbed. Both of these factors are useful indicators of sediment transport. Inman and Rusnak (1956), De Alteris et al. (1975), Gillie (1979) and Davidson-Arnott and Askin (1980) have all used rods to investigate depth of disturbance in nearshore areas.

In the present study three sites were set up to investigate depth of disturbance. The location of each site is shown in figure 3.8. At each site eight 10 mm diameter steel reinforcing rods were placed in a circle of 10 m radius. Each rod, 1.5 m long, was rammed into the bottom until approximately 0.5 m was left extending above the surface. An indicator disc was then placed over each rod to indicate the maximum depth of disturbance occurring between measurement periods. A thin cord connected all rods and at one point ran to the centre of the circle where it was connected to the mooring of a marker buoy. This enabled the site to be easily located, and then all of the rods to be easily located on the bottom. It was hoped that the sites could be measured on a monthly basis for at least 1 year but unfortunately this was not to be.

Site B was the first set up and initial measurements were made on 10 February 1981. This site was remeasured on 17 March 1981 but some time during the next month the buoy marking the site disappeared. With the buoy gone it was impossible to relocate the rods and so the site was lost. The one set of data that was obtained showed that from 10 February to 17 March there was an average accretion of 0.008 m at the site, an amount considered to be well within the measurement error. During the same period an average depth of disturbance of 0.11 m was measured. These data suggests that a layer of sediment 0.11 m thick was moving at the site but that no net erosion or accretion occurred. The data do not give any indication as to whether any net sediment transport occurred or, if it did, the direction of movement.

Site A was initially measured on 17 March 1981. As with site B the buoy marking the site went missing the following month and no data was obtained.

Site C was also initially measured on 17 March 1981. It was not possible to revisit the site until 9 June 1981. On this occasion the buoy rope was found to be cut part way through near the base but could not be replaced because the mooring had been buried. The mooring consisted of a 22.5 lt concrete filled bucket tied to two steel waratahs that had been rammed in beside the bucket. It is unlikely that this could sink into the bottom. The line linking the buoy line with the rods was found but the rods were not inspected because of the bad diving conditions.

Site C was next inspected on 7 October 1981. Again the buoy line disappeared into the bottom but this time there was no trace of any of the rods. It would therefore appear that in excess of 0.5 m accretion had occurred at the site. The most likely explanation for such accretion is that the crest of a large scale sand wave moved over the site. Because the buoy line was irreplacable and there was a strong likelihood of it breaking it was cut off and the buoy retrieved. The site was therefore abandoned.

The system of rods had proved unsuccessful and so a new system was tried. On 21 October 1981 a 3 m long 50 mm diameter pipe was water jetted 1.2 m into the seabed near site C. A depth of disturbance plate was placed over the pipe and a buoy line was then attached to the top of the pipe. The seabed elevation and the depth of disturbance were measured on four occasions over the following 5 months. Measurements ceased at this point because the buoy went missing.

Changes in the seabed elevation are shown in figure 3.16. The period was characterised by erosion with

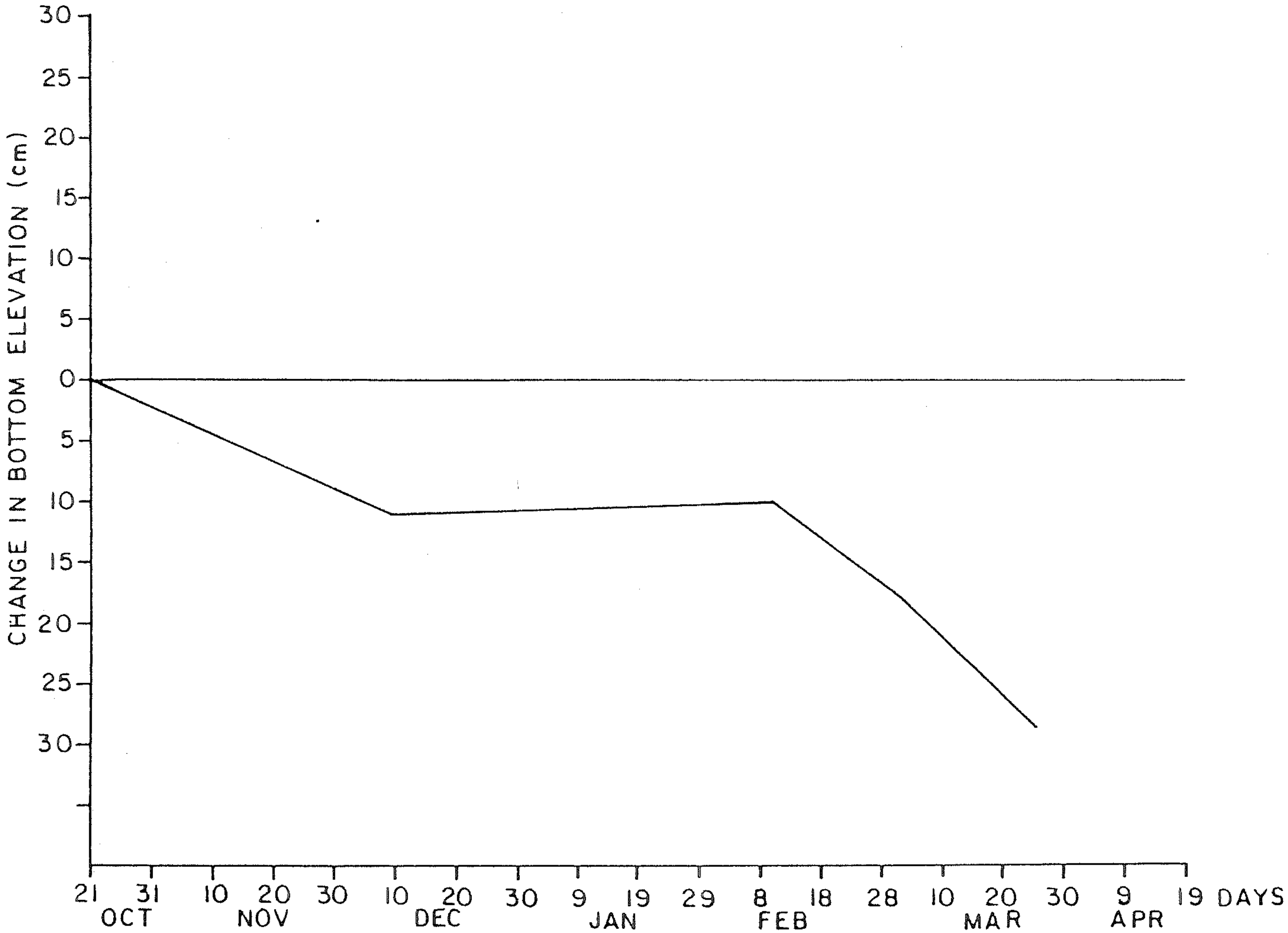


FIGURE 3.16 CHANGES IN THE SEABED ELEVATION NEAR SITE C FROM 21 OCTOBER 1981 TO 26 MARCH 1982.

one period of slight accretion. No depth of disturbance was recorded during the period so that the erosion measured was the maximum that occurred. The results are consistent with the theory that a large sand wave was moving over the site causing accretion and then erosion as the crest of the sand wave passed.

3.6 IMPLICATIONS FOR SEDIMENT TRANSPORT

3.6.1 Limit Of Significant Sand Transport

In a study of sediment transportation on the inner continental shelf it is useful to have an estimate of the seaward limit of significant transport. Hallermeier (1981a,b) presents a procedure for calculating this limit based on wave and sediment characteristics.

Hallermeier divides the on-offshore profile into three zones, shown diagramatically in figure 3.17. The littoral zone extends from shore to the seaward limit ($d\ell$) of intense sediment transport and extreme bottom changes. The shoal zone extends from $d\ell$ to a water depth (di) where expected surface waves are likely to cause little sediment transport. In this zone waves have neither a strong nor negligible effect on the bed. The offshore zone, extending seawards from di, is an area where surface wave effects on the bed are usually negligible.

Calculation of the water depths $d\ell$ and di requires data on median and extreme wave conditions and typical

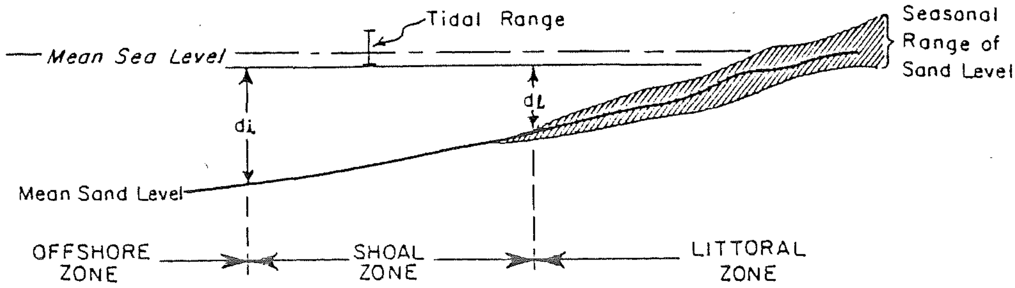


FIGURE 3.17 PROFILE ZONATION OF HALLERMEIER (1981a,b).

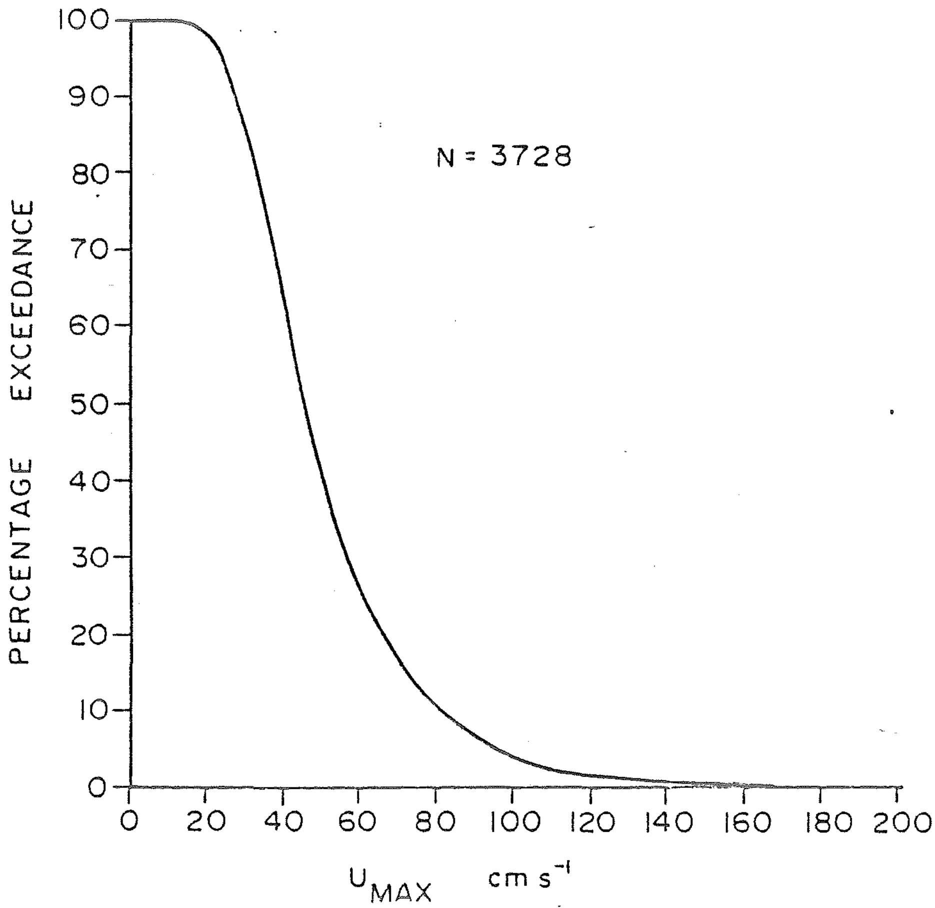


FIGURE 3.18 U_{max} PERCENTAGE EXCEEDANCE AT THE 7 M ISOBATH FOR THE PERIOD 7 OCTOBER 1981 TO 12 OCTOBER 1982.

sediment characteristics in the shoal zone. The median and extreme wave conditions are calculated from at least one full year of significant wave height data by assuming that the data fits a modified exponential distribution (see U.S. Coastal Engineering Research Center 1977, equation 4-6, p. 4-35). The limits $d\ell$ and $d\hat{\imath}$ are calculated from relationships giving the threshold flow energy for two distinct wave interactions with a sand bed. The first threshold is calculated for extreme wave conditions and the second for median wave conditions. In both cases linear wave theory is used to calculate near-bottom maximum horizontal currents. The limit of $d\ell$ is independent of sediment size while the limit $d\hat{\imath}$ is dependent on sediment size.

Hallermeier (1981 b) found that calculated shoal zones were in general agreement with other measurements of the seaward limit of significant transport, although there were several areas of uncertainty. The main area of uncertainty existed when $d\hat{\imath}$ exceeded 20 m which was usually considered the maximum limit for significant wave-induced transport.

Hallermeier (1981 a) presents a calculator program for computation of the water depths $d\ell$ and $d\hat{\imath}$. This program was modified for use on a "Hewlett-Packard 34C" calculator and then used to calculate $d\ell$ and $d\hat{\imath}$ at Timaru. The input data used was $\overline{H}_s = 0.968$ m, $\sigma = 0.437$ m, $\overline{T}_s = 10$ s and D = 0.0947 mm. The limits calculated were $d\ell = 7.04$ m and $d\hat{\imath} = 37.10$ m.

The littoral zone, with significant sediment transport, therefore extends out to the 7 m isobath which occurs approximately 1 km offshore in the area north of the port (see fig. 3.1 (b)). The shoal zone, for very fine sand, extends from the 7 m isobath out to the 37 m isobath which occurs approximately 20 km offshore.

Although the zone limits are only approximations they do indicate that considerable sediment transport, independent of sediment size, can be expected in the study area out to about the 7 m isobath and that the remaining area is subject to significant sand transport.

3.6.2 Magnitude Of Current Velocities

In order to obtain some idea of the magnitude of wave-induced oscillatory currents in the study area linear wave theory was used to calculate maximum horizontal oscillatory velocities, U_{max}, occurring under waves at the 7 m isobath. The appropriate equation is presented in appendix 2. Recorded values of H_s and T_s were used as inputs for the calculations. The average value, $\overline{U}_{max}$, was 51 cm s^{-1}. Figure 3.18 shows a percentage U_{max} exceedance curve for the period 7 October 1981 to 12 October 1982. For 50% of the time U_{max} exceeded 42 cm s^{-1}.

Linear wave theory assumes a symmetric wave which produces a flow of equal magnitude under both the crest and trough. In reality waves in shallow water are asymmetric with a steep crest and a shallow trough. Currents beneath the waves become asymmetric also, with a larger magnitude flow beneath the crests. Stokes' second order wave theory, which is applicable for most of the time at the 7 m isobath, was used to calculate differences between crest and trough velocity for the full set of wave data. The appropriate equation is presented in appendix 2. A mean difference of 20 cm s^{-1} was obtained, that is, the crest velocity was an average 20 cm s^{-1} greater than the trough velocity.

Stokes' theory also predicts a continuously increasing net particle displacement in the direction of wave propagation. The distance a particle is displaced during one wave period, when divided by the wave period, gives a mean drift velocity called the mass transport velocity (U.S. Coastal Engineering Research Center 1977, p. 2-38). Mass transport velocity was calculated for the 7.0 m isobath from the full set of wave data. A mean value of 2 cm s^{-1} was obtained. This value adds to the asymmetry of the wave-induced oscillatory currents.

If the theoretical currents are to be believed then wave-induced currents are much more important for sediment transport than any other current. The average magnitude of the maximum wave-induced oscillatory currents, $\overline{U}_{max}$, is on average five times greater than the tidal current and even the average asymmetry between the crest and trough is twice the magnitude of the tidal current. Coastal currents are negligible and the magnitudes of direct wind currents and density currents are probably very much smaller than those of the wave-induced oscillatory currents.

3.6.3 Threshold Exceedance

Komar and Miller (1973, 1975a,b) present equations for the calculation of threshold velocities required for sediment entrainment under oscillating wave-induced currents. The equations are based on empirical relationships derived from laboratory studies and there is a total lack of field data. A computer program is presented in Komar and Miller (1975a) to enable easy calculation of the threshold velocities. The threshold velocities were found to increase with increasing grain size or increasing wave period. Only oscillatory currents are considered, whereas, on the seafloor, unidirectional currents are also likely to be present. In a recent laboratory study on the threshold of sand-sized sediment under the combined influence of unidirectional and oscillatory flow Hammond and Collins (1979) found that thresholds increased with increasing grain size or decreasing wave period. This study was again limited by a total lack of field data.

Despite these limitations it was decided to use the computer program from Komar and Miller (1975a) to calculate the threshold velocities for a variety of sediment sizes. The results are presented in table 3.10.

The theoretical wave-induced currents calculated from linear wave theory for the 7 m isobath were compared by computer with the calculated threshold values and the percentage of time that the threshold was exceeded for each size class was determined. Table 3.11 shows the results

TABLE 3.10 THRESHOLD VELOCITIES FOR A VARIETY OF GRAIN SIZES AND WAVE PERIODS AS CALCULATED FROM KOMAR AND MILLER (1975a). VELOCITIES ARE ROUNDED TO THE NEAREST CM S^{-1}.

WAVE PERIOD (s)	GRAIN SIZE (MM) AND SIZE CLASS						
	0.09 VERY FINE SAND	0.18 FINE SAND	0.35 MEDIUM SAND	0.71 COARSE SAND	1.41 VERY COARSE SAND	2.83 GRANULE	8.88 PEBBLE
5	12	15	19	29	39	53	86
6	12	16	20	30	40	54	88
7	13	17	21	30	41	55	90
8	14	17	22	31	42	56	92
9	14	18	23	32	42	57	93
10	15	19	24	32	43	58	95
11	15	19	24	32	44	59	96
12	16	20	25	33	44	60	97
13	16	20	26	33	45	60	98
14	17	21	26	34	45	61	99
15	17	21	27	34	46	61	100
16	17	22	28	34	46	62	101
17	18	22	29	35	47	63	102

TABLE 3.11 PERCENTAGE THRESHOLD EXCEEDANCE AT THE 7 M ISOBATH FOR THE PERIOD 7 OCTOBER 1981 TO 12 OCTOBER 1982.

	SIZE CLASS						
	VERY FINE SAND	FINE SAND	MEDIUM SAND	COARSE SAND	VERY COARSE SAND	GRANULE	PEBBLE
PERCENTAGE EXCEEDANCE	100.0	99.8	96.8	83.4	55.9	27.8	5.7

of this analysis. Transport of very fine sand, fine sand medium sand and coarse sand can potentially occur for greater than 80% of the time while, at the other end of the scale, pebbles can only be transported for approximately 6% of the time. These results were calculated for the 7 m isobath and sediment transport can be expected to increase shoreward and decrease seaward of this line.

3.7 SUMMARY AND CONCLUSIONS

The study area is mantled with a uniform layer of very fine sand with an occasional patch of gravel. Some finer sediments occur to the south of Timaru Harbour where deeper water occurs.

Using the technique of Hallermeier (1981a,b) it was suggested that the study area is characterised by intense sediment transport out to the 7 m isobath and that the remaining area is subject to significant sand transport. The study area is therefore divided into two transport zones. Kirk (1978), however, assumed a uniform transport zone when calculating the total transport through the area enclosed by the 11 m isobath. Gibb and Adams (1982) described an "outer nearshore transport zone" that extended seaward from the surf zone to depths of 30 - 60 m. They did not subdivide this zone in any way.

The bathymetry of the study area and the change in seabed elevation at site C suggest that some of the nearshore sediment transport may occur through the migration of large scale bedforms.

The hydraulic environment is dominated by wave-induced oscillatory currents which, at the 7 m isobath, are on average five times the velocity of tidal currents. The average asymmetry in the crest and trough velocities as calculated from Stokes' second order wave theory is twice the magnitude of the tidal currents. Coastal currents are negligible and direct wave currents and density currents are probably also relatively unimportant.

The calculated wave-induced currents at the 7 m isobath exceed the calculated thresholds for sediment entrainment for greater than 80% of the time for sand sizes up to coarse sand, 56% of the time for very coarse sand, 28% of the time for granules and 6% of the time for pebbles. These values can be expected to increase shoreward and decrease seaward of the 7 m isobath. Depth of disturbance in the area is likely to be at least 0.11 m and therefore there is a considerable volume of sediment potentially available for transport.

The predominant wave direction is from the east to south-east quadrant and sediment transport should therefore be predominantly north-west and shoreward. The tendency of wave refraction to bend wave crests parallel to the coast, particularly in shallow water, will mean a greater tendency for sediment to be transported in a shoreward direction.

Grain size data for the accreting Caroline Bay suggests that sediment is entering the Bay from the north and then sweeping around in an anti-clockwise direction.

The area immediately to the north-west of the North Mole is protected from the predominant waves and fine sediment has been deposited there. Grain size data for the seafloor sediments, however, gives no indication of sediment transport patterns. Sorting and skewness patterns simply follow the mean grain size and surface texture patterns.

The theoretical relationships studied and the depth of disturbance measurements indicate that there is potential for a significant amount of sediment transport to occur. The following chapters are devoted to direct measurement of this transport by artifical sediment tracing techniques. Attempts will be made to relate the measured transport with recorded wave conditions, calculated wave-induced currents and calculated percent threshold exceedance.

CHAPTER IV

SIMULTANEOUS TRACING OF A RANGE OF SEDIMENTS

4.1 INTRODUCTION AND AIMS

This chapter describes experiment 1, the first of four sediment tracing experiments undertaken during the present study. The experiment used the spatial integration technique to follow the movement of both fluorescent and magnetic tracer on the seafloor over a period of 2.3 months.

The fluorescent tracer was employed to obtain data on the rates and directions of movement of sediment ranging in size from very fine sand to pebbles. To the author's knowledge, this is the widest size range of sediment used in a single fluorescent tracing experiment to date. Not only did the fluorescent tracer provide data on sediment transport rates and directions for a variety of sediment sizes but it also enabled the differential transport or sorting of the various size fractions to be studied. Ingle and Gorsline (1973, p. 133) state:

> The sorting of grains of differing diameter and/or specific gravity ultimately dictates the basic changes and indeed the existence of any given sand beach. Thus, differential transport of various grain sizes constitutes one of the most fundamental processes taking place in the nearshore environment if not the most critical process in terms of beach formation.

Sorting processes such as those referred to by Ingle and Gorsline are not only important with respect to the formation of sand beaches but are of equal importance in the formation of coarse grained beaches. The fact that sorting occurs on coarse grained beaches has already been demonstrated in chapter 2 which described the separation of the coarse beach sediments and the fine nearshore sands at Timaru.

Fluorescent tracers provide an ideal tool for field studies using different sized sediments. The various size fractions can be labelled with different coloured dyes before release or, alternatively, the recovered samples can be sieved before analysis. The first method has been employed by Jolliffe (1964), Yasso (1965), Ingle (1966), Vernon (1966), Murray (1967), Boon (1968), Cook (1969), Harrison et al. (1970) and Fox (1978). The second method employing sieving has been used by Schwartz (1966, 1967), Ingle and Schnack (1975), Komar (1977) and Duane and James (1980). Most of these studies have been carried out on beaches and only Vernon (1966) and Cook (1969) have studied the simultaneous movement of various grain sizes on the continental shelf.

Vernon (1966) carried out tests using two sand size grades with median diameters of 0.25 and 0.42 mm. In some experiments an additional sand size grade with a median diameter of 0.1 mm was also used. Successful tests were carried out in water depths ranging from 2.4 - 18 m over periods of several hours to several months. The most common pattern of movement was one of slow onshore transport of all grain sizes tested. Fine sand always moved more rapidly than the coarse sand and transport was greatest in the shallowest water depths. Only a few tests showed positive offshore movement of tracer sand and in these cases the bottom slope was substantially greater than at other test sites. Vernon interpreted his results as supporting the null point theory proposed by Cornaglia in Zenkovich (1967, p. 101).

Cook (1969) found that small scale bedforms altered the transport behaviour of sands and enabled all available grain sizes to be transported with equal facility. Cook concluded that wave generated currents do not sort sand but cause the entire grain population to migrate as a unit.

The magnetic tracer used for the present experiment was ironsand, which had a high percentage of heavy minerals and could be detected by its magnetic properties. The ironsand was employed for three reasons. Firstly, to see if it was suitable as a sediment tracer; secondly, to compare the movement of sediments with differing specific gravities; and, thirdly, to determine whether any differential movement could be related to the concept of hydraulic equivalence. The concept of hydraulic equivalence was described by Rittenhouse (1943, p. 1741) in the following statement:

> ...whatever the hydraulic conditions may be that permit the deposition of a grain of particular physical properties, these conditions will also permit deposition of other grains of equivalent hydraulic value.

One of the physical properties of particular importance with respect to sediment transport is settling velocity. Settling velocity can be measured in the laboratory or calculated from theoretical equations. Using settling velocities it is possible to predict the relative behaviour of different sediment types from grain size and specific gravity data. This prediction was made for the fluorescent tracer and the ironsand used in this experiment and it was assumed that any difference in behaviour from that predicted would be attributable to other physical properties of the sediments, such as particle shape and arrangement on the seabed.

The only other studies known to have used magnetic tracers are Pantin (1961), Hartke in Ingle and Gorsline (1973), Wright, Cross and Webber (1978, 1979) and Matthews (1980b).

To summarise, the aims of this experiment were:

a) To determine both the rate and direction of transport of sediment ranging in size from very fine sand to pebbles.

b) To compare the transport of the various size fractions.

c) To look for relationships between the measured sediment transport rates and wave and wave-dependent parameters.

d) To assess the use of ironsand as a sediment tracer by using its magnetic properties to distinguish it from "native" non-magnetic sediment.

e) To compare the movement of sediments having different specific gravities that have been exposed to the same conditions on the seafloor.

f) To see if any differences in movement between the sediments of different specific gravities could be predicted from settling velocities, given grain size and specific gravity data.

4.2 LOCATION OF THE EXPERIMENT

Figure 3.8 shows the site chosen for experiment 1. It is approximately 2 km to the north of Timaru Harbour and 1.4 km offshore, in a water depth averaging 7.6 m. This site is just seaward of the limit of intense sediment transport as determined in section 3.6.1 and it was chosen because it is seaward of the barrier beach enclosing Washdyke Lagoon where a later experiment was performed.

4.3 PREPARATION OF TRACER MATERIAL

4.3.1 Ironsand

Approximately 90 kg of ironsand was obtained from Carters Beach, Westport. This sand has a high percentage of heavy minerals (specific gravity greater than 2.85 g cm^{-3}) and required no preparation prior to release on the seafloor. Samples of the sand were retained for subsequent analysis of grain size, specific gravity and magnetic properties.

4.3.2 Fluorescent Tracer

Techniques for labelling sediment with fluorescent dye are outlined by Russell (1961), Wright (1962), Yasso (1962, 1966), Ingle (1966) and Teleki (1966). Most of these techniques involve dispersing a fluorescent pigment in a thinner, adding an adhesive and then mixing with sediment. The resulting compound is then spread out to dry. The material dries in aggregates and crushing is required to separate individual grains. The crushed material is then sieved to produce the desired grain size.

The technique of Wright (1962) does not involve using an adhesive. Wright found that anthracene, a brilliantly fluorescent material, would adhere to the surface of the grains. This eliminated the problem of particles aggregating on drying and also had the added advantage that the thickness of the coating added was extremely small. Ward and Sorensen (1970) attempted to use Wright's labelling technique for tracing experiments on the Texas Gulf Coast. They found that the anthracene coating did not have adequate durability under tests in the field and the laboratory and so they reverted to using the technique of Yasso (1966) which employs a resin to bind the pigment to the grains. It appears, therefore, that an adhesive is required for satisfactory labelling.

Kirk *et al.* (1974) at the Department of Geography, University of Canterbury, built a fluorescent dyeing machine to streamline the dyeing procedure by curing and crushing the labelled sand simultaneously, hence preventing aggregates forming. The machine, "Throtnungler", was not well sealed and a considerable amount of fluorescent dye escaped when the machine was operating. For this and other reasons the machine was dismantled (Dr R M Kirk, Department of Geography, University of Canterbury 1983, pers. comm.). For the present study it was decided to build a new version of the dyeing machine, with increased efficiency, to enable large quantities of fluorescent tracer to be easily produced.

Figure 4.1 shows the dyeing machine and its major components. The heating unit (1) provides air at 70°C which is blown by the air blower (2) into the plastic drum (3). The drum, which rotates at 24 r.p.m., is lined with baffles (4) and contains a number of 25 mm diameter steel rollers (5). Sediment, fluorescent pigment, lacquer (the adhesive) and thinner are placed in the drum which is then rotated with the hot air blowing until the thinner has been evaporated and the pigment is stuck firmly to the grains. The steel rollers and the baffles ensure the particles are kept separate until the drying is complete. The machine is mounted on a trolley (6) and is easily moved about. For the present study all dyeing was done outdoors to allow dispersion of the fumes from the thinner which are both toxic and inflammable.

The quantities of fluorescent pigment, lacquer, and thinner used depended on the grain size of the sediment being dyed. The quantities used for fine sands and for pebbles are shown in table 4.1. Only approximate quantities

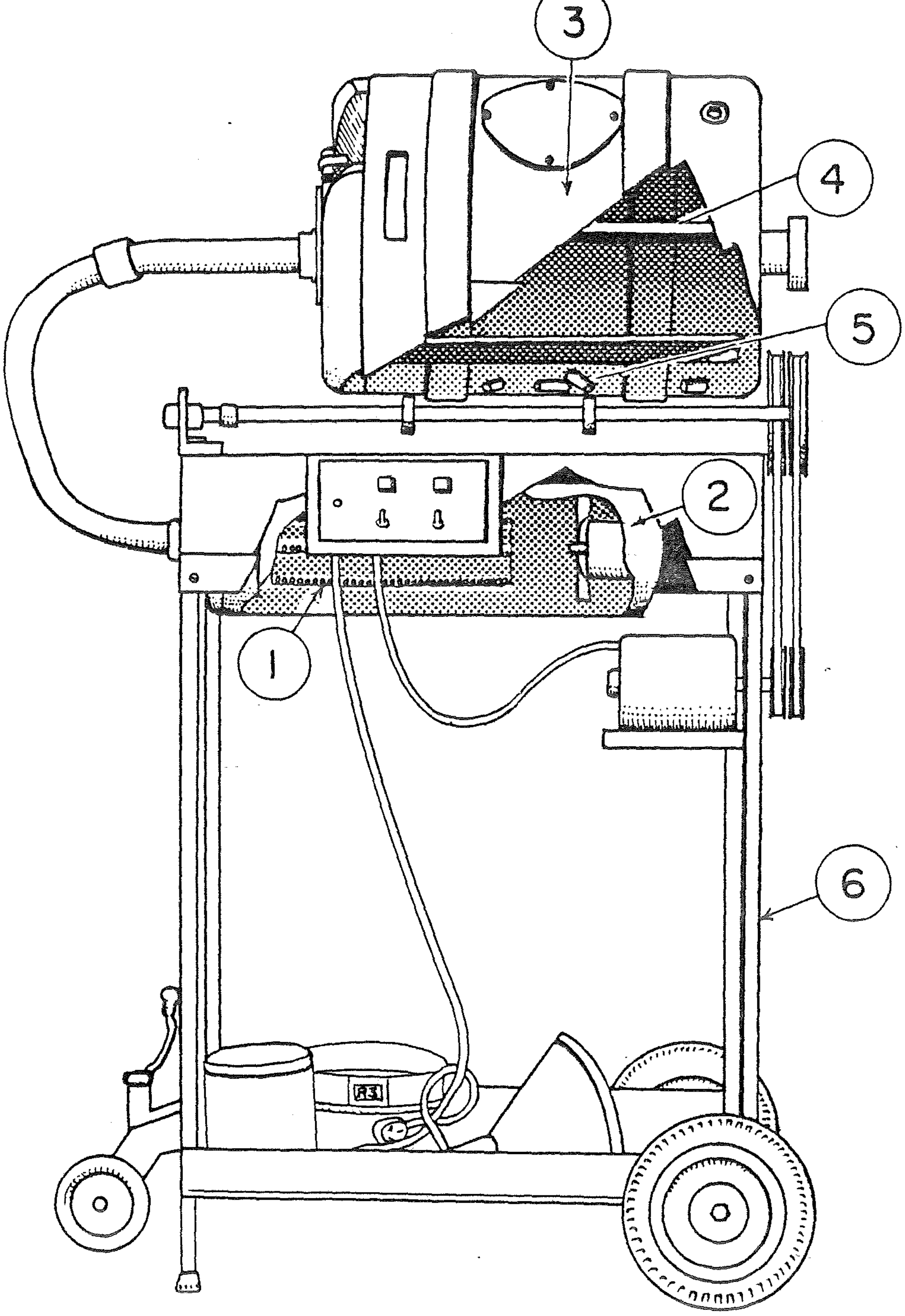


FIGURE 4.1 FLUORESCENT DYEING MACHINE.

(1) HEATING UNIT
(2) AIR BLOWER
(3) PLASTIC DRUM
(4) BAFFLES
(5) 25 MM DIAMETER STEEL ROLLERS
(6) TROLLEY

were required and for intermediate sizes intermediate quantities were used. Drying time varied from 25 - 60 minutes, depending on the ambient temperature and the size of sediment being dyed. Coarse sediment dried much faster than fine sediment.

TABLE 4.1 QUANTITIES OF FLUORESCENT PIGMENT, LACQUER, THINNER AND SEDIMENT USED FOR FLUORESCENT DYEING.

a) For Fine Sands

	WEIGHT (g)	WEIGHT RATIO	VOLUME (cm^3)	VOLUME RATIO
Fluorescent Pigment[1]	50	1	135	1
Lacquer[2]	380	8	442	3
Thinner[3]	630	13	735	5
Sediment	6000	120	6280	47

b) For Pebbles

	WEIGHT (g)	WEIGHT RATIO	VOLUME (cm^3)	VOLUME RATIO
Fluorescent Pigment[1]	35	1	100	1
Lacquer[2]	160	5	185	2
Thinner[3]	490	14	565	6
Sediment	6000	171	4710	47

1 "Fluorescent orange pigment K459" obtained from Morrison Printing Inks And Machinery Limited, 351 Selwyn Street, Christchurch.

2 "Dulon Tinter 575-9236" (Clear) obtained from Dulux New Zealand Limited, PO Box 119, Christchurch.

3 "Toluene" obtained from Shell Oil New Zealand Limited, Lyttelton.

One of the aims of the present experiment was to trace a wide size range of sediment. The lower size limit was set at 0.0625 mm, the lower boundary of very fine sand on the Wentworth (1922) scale, because below this size the counting of fluorescent grains becomes very difficult. The upper size limit was set at 19.050 mm because this corresponded with an available sieve size and sediment larger than this would not easily fit into the core tubes that were used for sampling.

Sediment for dyeing was obtained from three sources. Coarser sediments were obtained from South Beach, fine sandsfrom beaches around Christchurch, and very fine sand from Caroline Bay. It was hoped that at least 50 kg of sediment could be dyed for each size class but a shortage of medium sand meant a much lesser quantity of this size was dyed. All sediment for dyeing was transported to the Physical Laboratory, Department of Geography, University of Canterbury where it was washed to remove salt and any extraneous material and then air dried. The sediment from South Beach was hand sieved into three groups, less than 5.6 mm, 5.6 - 9.5 mm and 9.5 - 19.05 mm. The sediment was then dyed in the dyeing machine.

Samples of dyed sediment were taken and sieved to determine the percentage of sediment falling into each size class. Table 4.2 shows the final quantities that were obtained.

TABLE 4.2 QUANTITIES OF FLUORESCENT DYED SEDIMENT PRODUCED FOR EXPERIMENT 1.

GRAIN SIZE (MEDIAN DIA. MM)	SIZE CLASS	AMOUNT
0.063 - 0.125	Very Fine Sand	51
0.125 - 0.250	Fine Sand	91
0.250 - 0.500	Medium Sand	16
0.500 - 1.000	Coarse Sand	59
1.000 - 2.000	Very Coarse Sand	60
2.000 - 4.000	Granules	67
4.000 - 19.050	Pebbles	61
	TOTAL	405 Kg

Several tests were carried out to test the resistance of the tracer particles to abrasion. One hundred gram samples of very fine sand, 1.0 mm particles and 2.0 mm particles were placed separately with water in a container and subjected to 30 minutes mixing with a milkshake machine. Although some dye washed into the water the particles all retained their fluorescent property. Two tests were carried out for coarser particles. In the first test thirty dyed pebbles - ten 9.5 + mm, ten 9.5 mm and ten 4.0 mm - were placed in the drum of the dyeing machine with 6 kg of undyed sediment, approximately 9.5 mm in diameter, and rotated for 30 minutes. All but three of the 4.0 mm particles were still easily distinguishable both with and without the aid of an ultraviolet light. The three missing particles were probably crushed during the rolling process. In the second test thirty dyed pebbles ranging in size from 4.0 - 19.05 mm were placed with 10 kg of undyed pebbles in the drum of the dyeing machine and seawater was added. After rotating the drum for 30 minutes the material was inspected and all the dyed pebbles were found to be easily distinguishable from the unlabelled pebbles. The dyed sediment was therefore considered sufficiently resistant to abrasion to be used in the natural environment.

Some dyed material was placed in seawater for one week to test for long-term leaching. No leaching occurred during this period and it was concluded that the dye was stable in salt water.

4.4 SAMPLING GRID

Both the rates and directions of movement of tracer in this experiment were to be determined by the spatial integration technique. This technique requires samples to be collected from the area surrounding the dump site at various times after the material is released. By determining the concentration of tracer material in each sample dispersion diagrams can be drawn up and the average rate and direction of movement determined.

Options for accurate position fixing at the tracer site included using a sextant, using the "Decca

Trisponder System" or by the placement of a rope grid on the seafloor. The final option was chosen for the following reasons:

a) The sextant would be difficult to operate accurately.

b) The accuracy of the trisponder (± 3 m) was sufficient for coarse spaced samples (greater than 10 m sample intervals) but could not be used to sample accurately in the area immediately surrounding the dump site.

c) The trisponder would require considerable setting up on the boats to be used for sampling and may not always have been readily available.

d) Operationally it would be much easier to obtain samples from semi-permanently located spots rather than by position fixing each time.

e) The same site could be re-sampled with greater accuracy by using the rope grid.

The rope grid constructed was of radial configuration and was similar in design to grids used by Boon (1968) and Kirk (1978). Figure 4.2 shows an outline of the grid. Sample points were indicated by knots tied in the lines so that they could be easily located when water visibility was poor. Each line was weighted and the end of each line and the centre point were marked with labelled buoys. The lines were constructed with the buoy line and weights attached. During placement the central anchor and attached buoy were dropped in place. The inner end of a line was then attached by a diver to the central

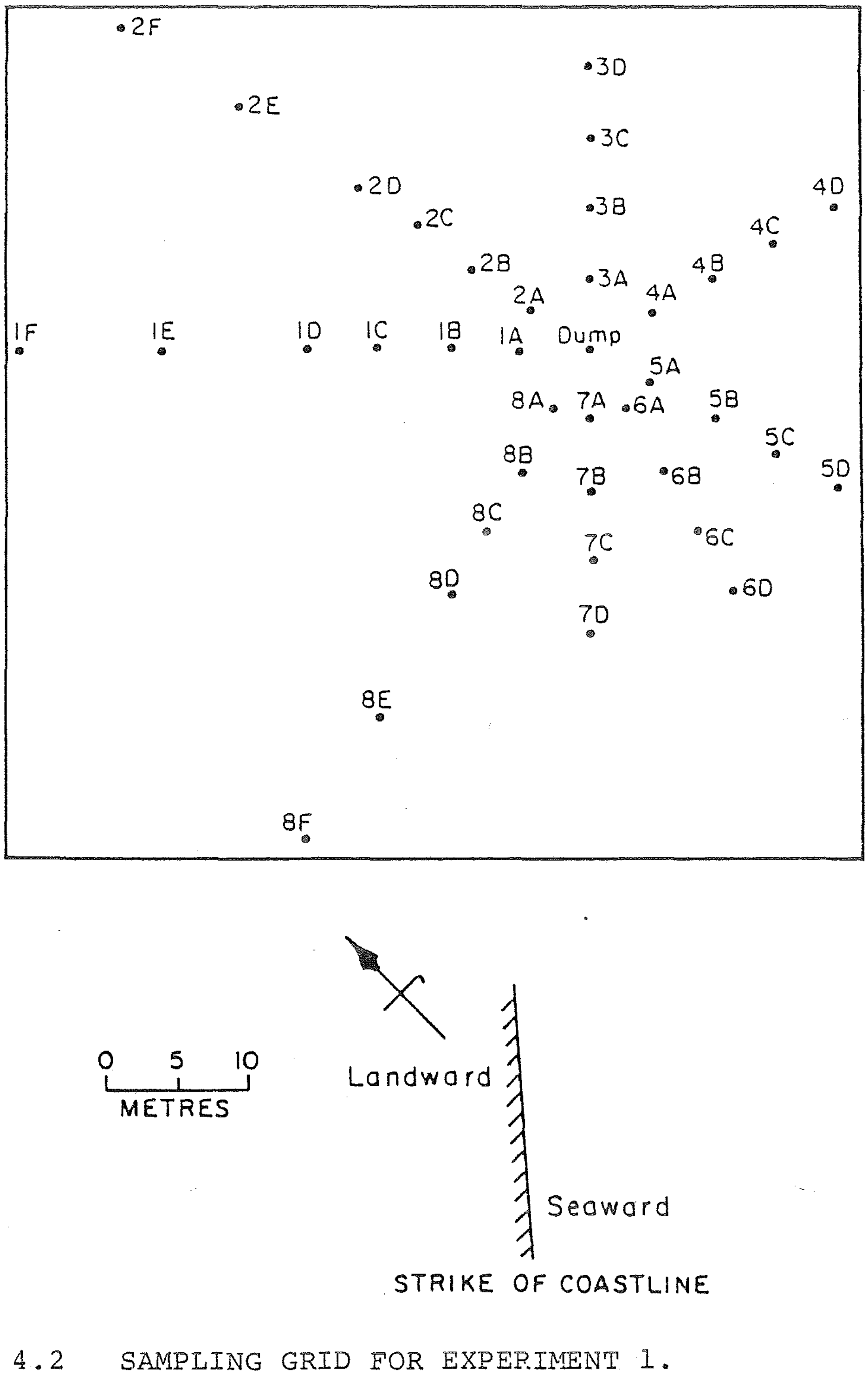


FIGURE 4.2 SAMPLING GRID FOR EXPERIMENT 1.

anchor with the remaining line and buoy line still on board the boat. Once the line was connected the boat motored out on a specified heading until all of the line and buoy line had been fed out. Considerable difficulty was experienced during this operation because while the diver was connecting the line to the central anchor the boat drifted off its heading and it was often difficult to regain the correct heading before all of the line had been fed out. This accounts for the irregular spacing of the grid lines as seen in figure 4.2. Once the grid had been placed steel reinforcing rods were rammed in at the end of each line and at the central anchor to prevent any possible dragging of the lines by the buoys. The final orientation of the grid was then determined by underwater compass.

4.5 RELEASE OF TRACER MATERIAL

Several methods have been employed for releasing tracer material on the seabed in offshore locations. Inman and Chamberlain (1959) used divers operating from a small boat to carry tracer sand to a release point in a plastic bottle. The bottle was then opened and the tracer sand poured onto the bottom. Vernon (1966) also used divers to carry small amounts (up to 7 kg) of tracer sand to the bottom in plastic bags or in a hard plastic container with a tightly fitting top. The divers then released the tracer on the bottom. When releasing larger amounts of tracer

Vernon simply dropped the material to the bottom in sturdy paper bags. Jolliffe (1963) tried to feed tracer sand down a flexible plastic tube to the seabed. This proved unsuccessful and Jolliffe ultimately used a box fitted with a weighted mechanical plunger that opened on contact with the seabed. Ingle (1966) reported that workers at the University of Southern California successfully used a modified oil drum fitted with a hinged false-bottom, rubber gasket and loose-line trip release to deposit over 2200 kg in approximately 30 m of water. Shrivastava (1970) also developed a modified oil drum with an opening false bottom that was capable of releasing more than 250 kg of tracer sand on the bottom at one time. Lees (1979) pumped a tracer slurry to the seabed through a 10 cm diameter pipe lashed to the side of a ship and terminating 40 cm above the seabed. Bruun and Purpura (1965), Murray (1967), Bruun (1969), Duane (1970) and Lavelle et al. (1978) have released tracer by dumping it in water soluble bags.

For the present study it was decided that the easiest method would be to use divers to release the tracer at the centre of the grid. This eliminated any problems of locating a boat over the exact release point and ensured that all sediment was released at the dump site. The tracer was placed in tins in lots of approximately 20 kg and the fluorescent dyed sands were then pre-wet with a mixture of water and detergent. Pre-wetting was done to release surface tension and prevent particles floating, and is common practice in fluorescent sand tracer studies (see for example Ingle 1966; Vernon 1966; Murray 1967; Ward and Sorensen, 1970; Goodwin 1975; Blackley 1980; Inman et al. 1981). The tins of tracer material were placed on board two small boats and taken to the tracer site. One of the boats tied up to the central buoy line and all tins were eventually transferred to this boat. The tins were filled with water, lids were fixed on and then they were lowered one at a time to the bottom accompanied by a diver who guided the tin to the dump site. The diver then removed the lid and tipped the tracer out. Some of the sand, however, had packed firmly in the tins and had to be scraped out. The fluorescent dyed coarse sediment was released first followed by the fluorescent dyed sand and finally the ironsand. Had the coarse sediment been released last it could have acted as a lag deposit and prevented movement of the finer sediment until current velocities were sufficiently strong to move the coarse material. The tracer material forred a mound on the seafloor which was approximately 0.4 m high and 1.0 - 1.5 m in radius.

Significant wave height during the release averaged 0.65 m and the significant period averaged 9 s. Within 30 minutes of the completion of the tracer release ripples had begun to form on the tracer mound. The author observed a small amount of sand being thrown into suspension by the wave-induced currents and in areas around the dump tracer sediment was seen to be concentrating on the crests of ripples.

4.6 SAMPLE COLLECTION

Sample collection methods for tracer studies in the nearshore fall into two types. Firstly, surface samples can be collected by using grease coated cards or strips, either pressed into the bottom by divers (Vernon 1966; Cook 1969; Harrison et al. 1970; Brattelund and Bruun 1975) or by lowering the cards on an attached weight (Jolliffe 1963; Ingle 1966). Secondly, volumetric samples can be collected either by using divers equipped with coring devices (Moore and Fry 1967; Kraus, Farinato and Horikawa 1981) or by using grab devices (Venkatesh 1974; Lees 1981).

Indications of depth of disturbance at site B and reference to the appropriate literature suggested that the mobile sediment layer at the tracer site could be in excess of 0.10 m (Courtois and Monaco 1969; Heathershaw and Carr 1977; Lees 1981). Surface samples would probably only retrieve a small portion of the total tracer at a sample point after initial mixing had begun. Because one of the basic requirements of a tracer study is to account for all of the tracer released (Greer and Madsen 1979) surface sampling would not be adequate for this experiment. In addition, detection of the ironsand required volumetric samples. Therefore volumetric samples were collected.

Samples were collected from the grid on seven occasions over a period of 2.3 months. An attempt to collect samples on a later occasion was abandoned because only one of the nine buoys marking the grid was still in position. Samples were collected in 0.30 m long, 0.05 m diameter, PVC tubes labelled for each point on the grid. The tubes were taken to the bottom by divers and driven vertically 0.20 m into the seabed with the aid of a hammer, although in some places less penetration was achieved due to the hard nature of the bottom. Before extracting a tube a lid was placed on the upper end so that suction would hold the sediment in during the extraction. Immediately after the tube was extracted it was tipped to prevent loss of sediment while the lower, open end was capped.

In addition to the grid samples, two cores were obtained on all but the first two sample runs. For these cores the core tube was driven in, in the usual way, and then rags were stuffed into the tube before placing the lid on the upper end. This excluded the water from the tube and prevented the sand from moving in the tube after extraction, thereby allowing the core to be kept intact until it was opened for analysis.

The author and another diver collected the samples, each working from a small boat and sampling four lines of the grid. Surface attendants placed the tubes and caps for a particular line, with the exception of the outer tube, into a netting bag. The bag and the outer tube were given to a diver who was then towed to the buoy marking the outer end of the line to be sampled. The diver then descended and began sampling. Starting on the outer end of the line eliminated any difficulty for the diver in selecting the correct line.

The first sample was obtained quickly because the tube was already selected. The diver then swam along the line, running it through his hand, until he felt the knot marking the next sampling point. The correct tube then had to be selected from the bag and it was this operation that often proved to be the most time consuming part of the sample collection because of the poor visibility. Once the sample was collected the diver moved on to the next sample point, repeating the operation until all samples had been obtained. He then swam to the central buoy and ascended to the surface where he was met by his service boat. The attendants exchanged the full tubes for empty ones for the next line and the whole procedure was repeated until all lines had been sampled. The author then collected the two cores. Operating in this way the 38 grid samples and two cores could be collected in approximately one hour.

Once back on shore all grid samples were transferred into plastic bags and labelled before being transported back to the Physical Laboratory, Department of Geography, University of Canterbury, for analysis. In total 266 grid samples and 10 cores were collected.

4.7 FLUORESCENT TRACER

This section is concerned only with the fluorescent tracer. The ironsand tracer is dealt with in section 4.8.

4.7.1 Analysis

Cores were extracted from their tubes with the aid of a plunger which pushed the core out the bottom of the core tube. Any tracer grains along the walls of the tube could only move upwards in the core and hence could not increase the apparent depth of mixing. Once extracted cores were cut longitudinally and inspected under an ultraviolet (UV) light. A note was made of the visible tracer distribution and then one-half of the core was divided into 20 cm sections. If the core was broken, it was often necessary to use larger sections than this. Each section was then treated as a separate sample and analysis was carried out as for grid samples.

Samples were washed to remove salt and organic material. If a large amount of organic material was observed washing was continued until as much of this as possible was removed. The samples were then spread on newspaper and air dried. Once a sample was dry it was weighed.

Because a wide size range of tracer had been used and because it was all dyed the same colour sieving was necessary to sort out the various size classes. A set of seven sieves was used to divide the samples into very fine sand, fine sand, medium sand, coarse sand, very coarse sand and granules as defined by the Wentworth (1922) size scale and into pebbles (4.00 - 19.05 mm). Most samples were too large to be sieved in their entirety so it was necessary to reduce the sample size. It was decided that simple sample splitting should not be used for the following reasons.

Firstly, the number of coarser dyed particles released was much less than the number of finer particles and so in order to achieve good sensitivity with the coarser sizes it was necessary to analyse as much coarse material as possible. Secondly, most of the samples were composed largely of unlabelled very fine sand from the seafloor, so that all of the coarse material in the samples could be handled by the sieves. Therefore the following procedure was employed:

1. The whole sample was passed through the 4.0 mm, 2.0 mm, 1.0 mm and 0.5 mm sieves by hand. All material coarser than 0.5 mm (coarse sand and coarser) was retained on these sieves.

2. Material that passed through the 0.5 mm sieve was repeatedly split using a sample splitter until approximately 100 gm remained.

3. The 0.250 mm, 0.125 mm and 0.063 mm sieves were added to the sieve stack.

4. The split fine material was placed in the sieve stack which was then shaken for 15 minutes on an Endecott "Endrock" test sieve shaker.

At this stage the sample had been divided into the correct size classes. Each sieve fraction (size class) was weighed, placed on a clean sheet of paper and taken into a dark room. Where concentrations were expected to be high, or the weight of the fraction was obviously greater than 2 gm, it was split a number of times using a micro-sample splitter before being weighed and placed on paper. In the dark room the samples were spread until they were one grain layer thick and the luminophors present were then counted with the aid of a UV light fitted with a magnifying glass. If the number of grains was greater than 300 the sample was split again, weighed and recounted.

Sample concentrations, except for pebbles, were expressed as the number of luminophors divided by the weight of sediment counted (luminophors g^{-1}). The value obtained was rounded to the nearest whole number, hence the cut-off point of 2 gm mentioned earlier. For pebbles, the concentration was taken simply as the number of fluorescent pebbles present in the whole sample.

Checks on the analysis and counting procedure were made to see what size errors might be introduced. One sample was split once after being passed through the coarse sieves by hand. One of the splits was analysed normally while the other was sieved later and analysed for material finer than coarse sand. The differences in the concentration values between the two were 3% for very fine sand, 2% for fine sand and 13% for medium sand. Another sample had a relatively high concentration of very coarse sand which was split once before counting. Both splits were weighed and counted and then concentrations were calculated. The difference between the concentration values was 21%. A third sample was analysed twice. Concentration values differed by 28% for very fine sand, 1% for fine sand, and were the same for medium sand and coarse sand. The errors introduced in the counting procedure can therefore be considerable at times but it is likely that underestimates and overestimates cancel each other to some degree and reduce the magnitude of the overall error.

Concentration values for grid samples were converted to logarithms and then used to draw dispersion patterns for each size class for each of the seven sample runs. The x and y co-ordinates of the centroid of each pattern were then calculated from:

$$x = \sum_{i=1}^{n} c_i x_i \Big/ \sum_{i=1}^{n} c_i \qquad 4.1$$

$$y = \sum_{i=1}^{n} c_i y_i \Big/ \sum_{i=1}^{n} c_i \qquad 4.2$$

where x and y = x and y co-ordinates of the centroid

x_i and y_i = x and y co-ordinates of the i th sample point

c_i = tracer concentration at sample point i

n = number of sample points

An average grain velocity V (magnitude and direction) for each size class for each sample run was calculated from the positional shifts of the centroid between successive sample runs.

For core samples a histogram was plotted showing the distribution of tracer with depth. With the exception of the pebble size class a concentration weighted depth E, taken to be a measure of the thickness of the mobile layer, was calculated from:

$$E = \sum_{i=1}^{n} c_i E_i \Big/ \sum_{i=1}^{n} c_i \qquad 4.3$$

where E = thickness of the mobile layer (m)

c_i = tracer concentration in the i th depth interval (luminophors g^{-1})

E_i = median depth of the i th depth interval (m)

n = number of depth intervals in the core

Transport rates were then calculated from:

$$q = VE \qquad 4.4$$

where q = sediment transport rate per unit width ($m^3\ m^{-1} day^{-1}$)

V = average grain velocity ($m\ day^{-1}$)

E = thickness of the mobile layer (m), taken as the average E calculated from the two cores taken on each sample run.

Unless otherwise stated, all sediment transport rates determined during this study are expressed as unit width transport rates.

Because no successful cores were obtained for the first two sample runs the average thickness of the mobile layer from sample run 3 was used in the calculation of sediment transport rates for the first two sample runs.

Data recorded by the wave recorder were used to determine average wave parameters, average calculated wave-induced currents and the percentage of time the threshold velocities given in table 3.10 were exceeded between each sample run. In addition $(\bar{H}_s)^2$ was taken as a measure of wave energy. Table 4.3 shows the parameters that were calculated. The parameter PER is size dependent and so values are given for each size class. Regression analysis was used to look for linear relationships for each size class, firstly between the average grain velocities and the wave and wave-dependent parameters and, secondly, between the sediment transport rates and the wave and wave-dependent parameters. The regression analysis was run using the "Statistical Package For The Social Sciences" program on the University Of Canterbury's "Prime 750" computer.

TABLE 4.3 WAVE, CURRENT AND THRESHOLD EXCEEDANCE PARAMETERS CALCULATED FOR THE PERIOD BETWEEN EACH SAMPLE RUN, EXPERIMENT 1.

PARAMETER		DEFINITION
$\bar{H}_s$	:	Average H_s between sample runs
$\bar{T}_s$	:	Average T_s between sample runs
$(\bar{H}_s)^2$	:	Average H_s between sample runs squared
$\bar{H}_{rms}$	:	Average H_{rms} between sample runs
$\bar{H}_{max}$	:	Average H_{max} between sample runs
$\bar{U}_{max1}$	:	Average U_{max1}, determined from linear wave theory, between sample runs (see appendix 2).
$\bar{U}_{max2}$	:	Average U_{max2}, the second term in the calculation of U_{max} from Stokes' second order wave theory, between sample runs (see appendix 2)
$\bar{U}_{max3}$	:	Average U_{max3}, the current under the crest of a wave as determined from Stokes' second order wave theory, between sample runs. $U_{max3} = U_{max1} + U_{max2}$
$\bar{U}_{max4}$	:	Average U_{max4}, the current under the trough of a wave as determined from Stokes' second order wave theory, between sample runs. $U_{max4} = U_{max1} - U_{max2}$
PER	:	The percentage of time the threshold velocity for a given grain size is exceeded by U_{max1} between sample runs.

4.7.2 Results

Dispersion patterns for very fine sand, fine sand, medium sand, coarse sand, very coarse sand and granules are shown in figures 4.3 - 4.8 respectively. The calculated tracer centroid has been included on each pattern. The line passing the dump site on each dispersion pattern runs parallel to the coastline and divides the pattern into landward and seaward areas. Figure 4.9 shows the number of pebbles found and their location for each sample run. For sample run 7 the five pebbles that were found in the core taken at sample point 1B are included on the diagram although no pebbles were found in the ordinary grid sample taken at this point. Because of the small number of pebbles found no contours were drawn.

Figure 4.10 shows plots of the tracer centroid movement over time for very fine sand, fine sand, medium sand, coarse sand, very coarse sand and granules.

Histograms showing the tracer distribution with depth calculated from the available cores are shown in figures 4.11 - 4.17 for all size classes. The calculated thickness of the mobile layer, E, is shown on each histogram for all size classes except pebbles. Missing cores indicate that no sediment of that particular size class was present in the core. For example, pebbles were only found in core 1B from sample run 7.

Time between sample runs, centroid displacement, average grain velocity V, average thickness of the mobile layer E and sediment transport rate q are presented in tables 4.4 - 4.9 for each sample run for very fine sand, fine sand,

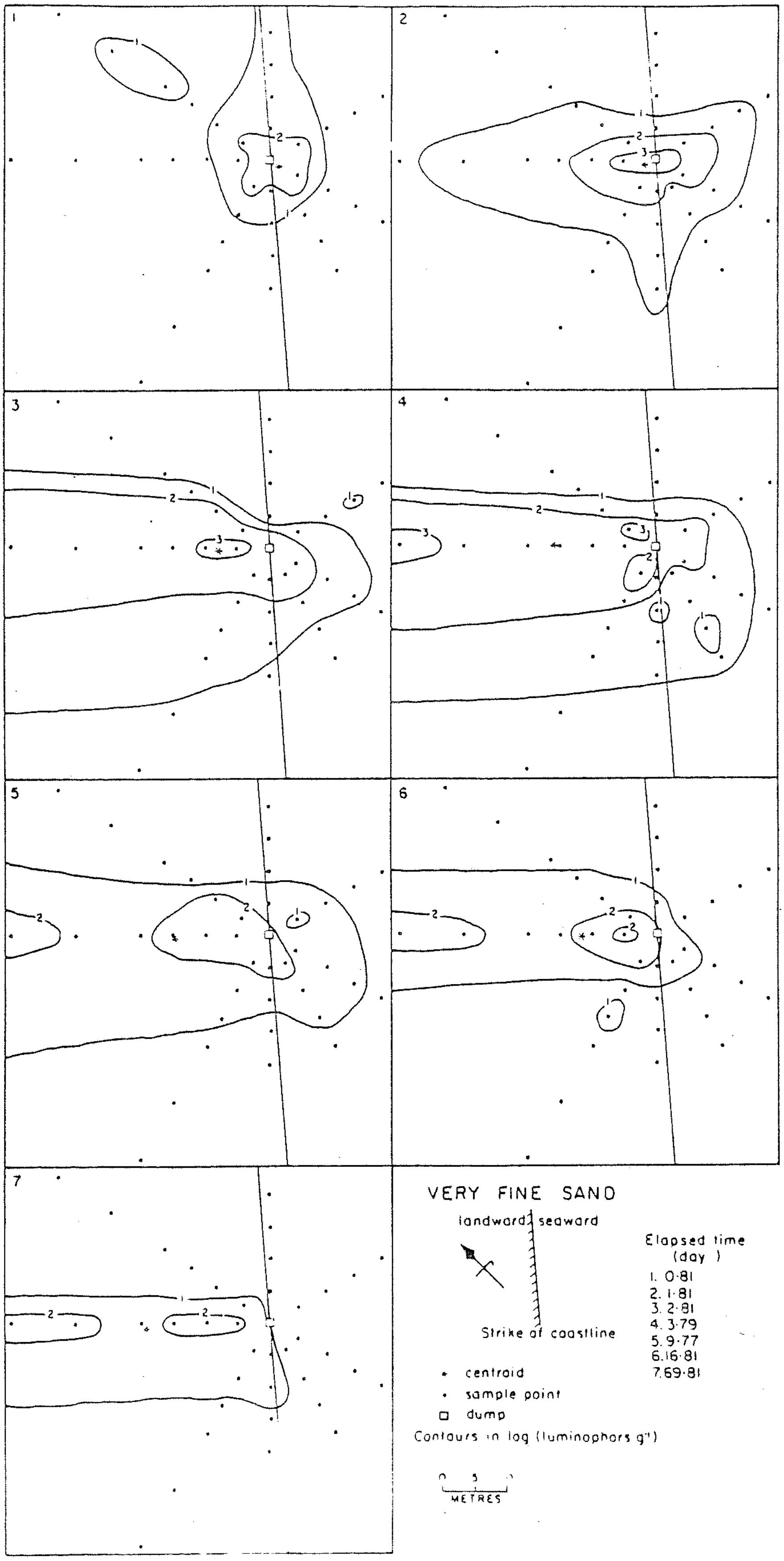


FIGURE 4.3 FLUORESCENT TRACER DISPERSION PATTERNS FOR VERY FINE SAND, EXPERIMENT 1.

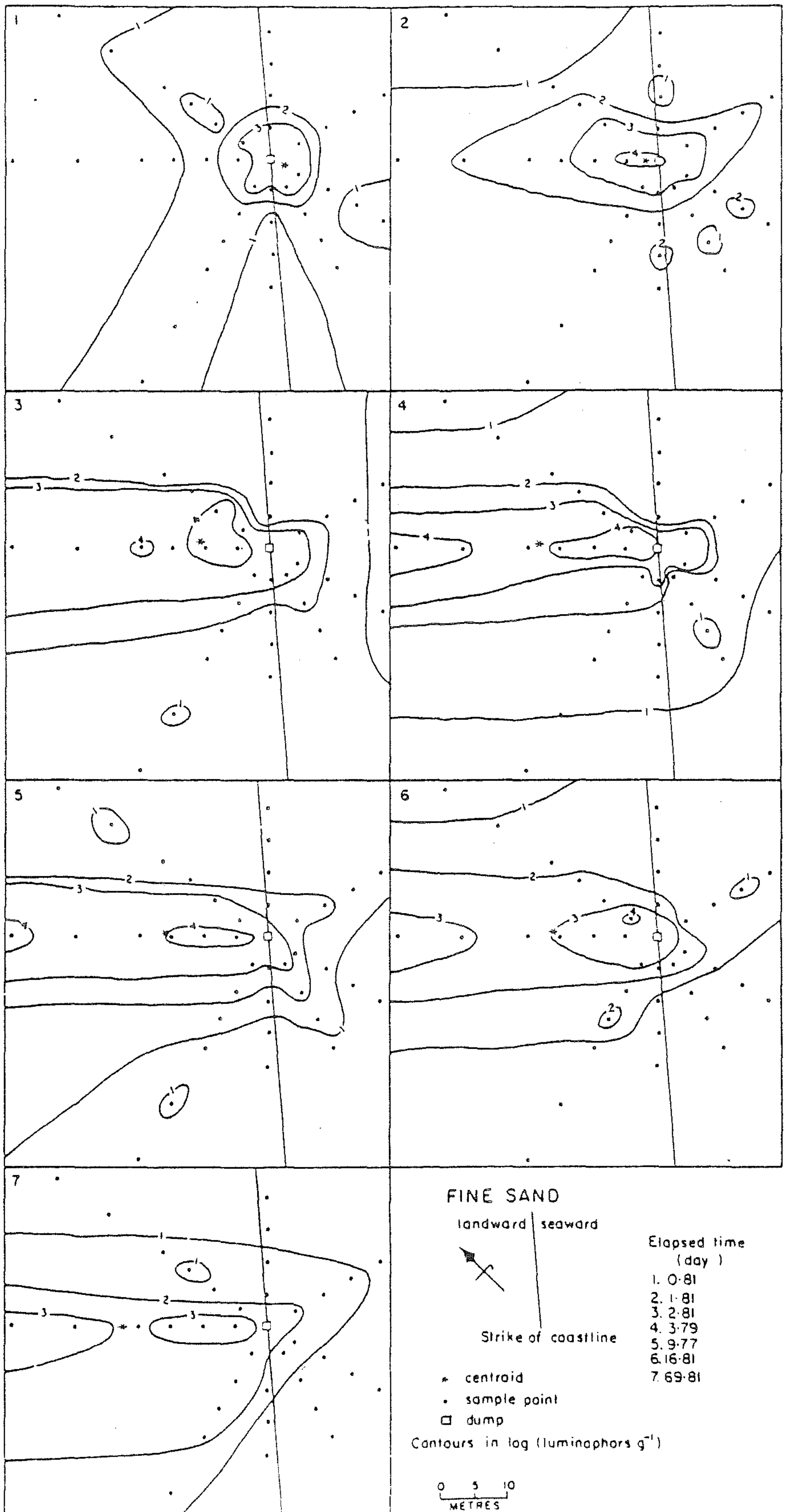


FIGURE 4.4 FLUORESCENT TRACER DISPERSION PATTERNS FOR FINE SAND, EXPERIMENT 1.

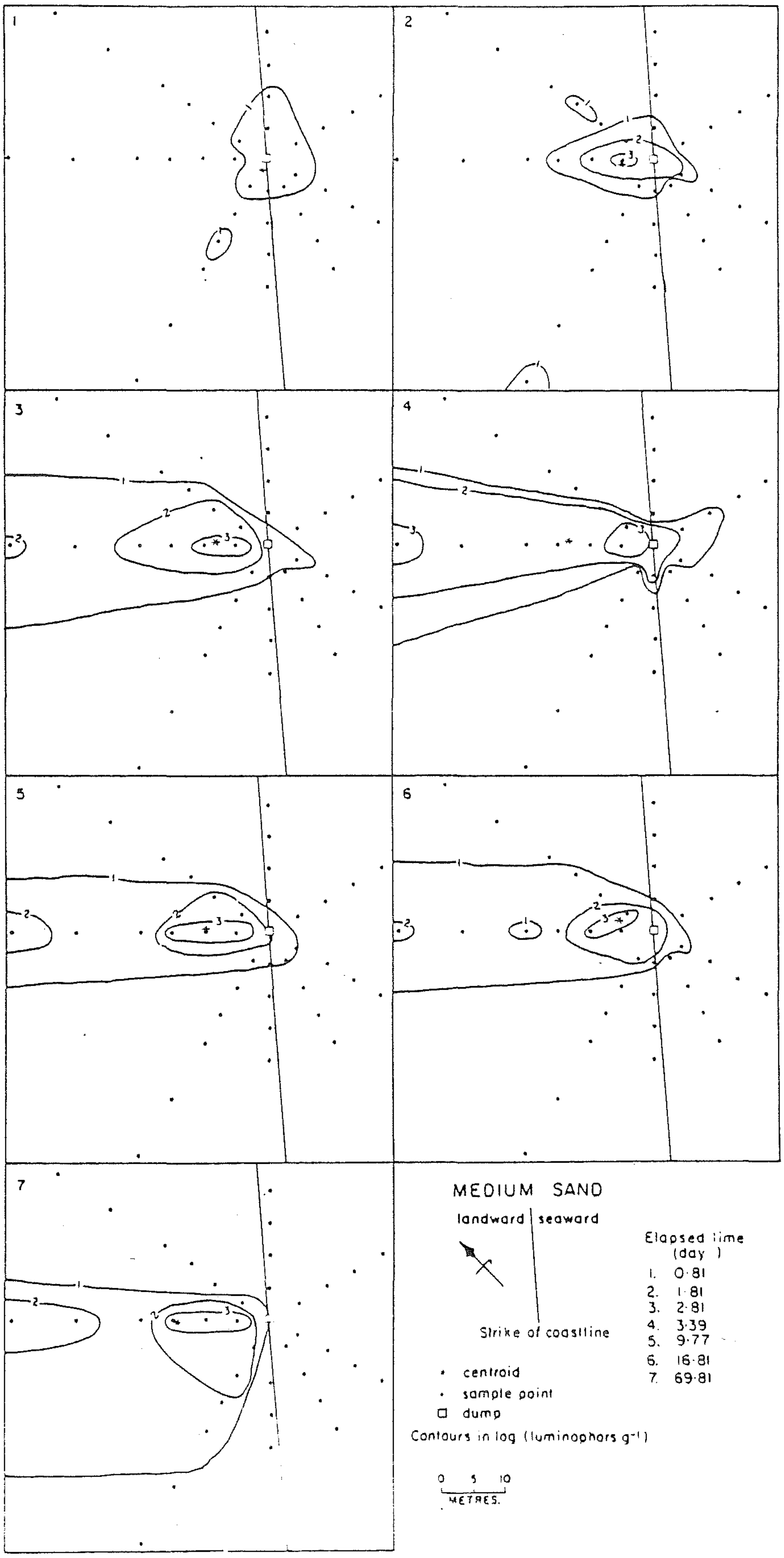


FIGURE 4.5 FLUORESCENT TRACER DISPERSION PATTERNS FOR MEDIUM SAND, EXPERIMENT 1.

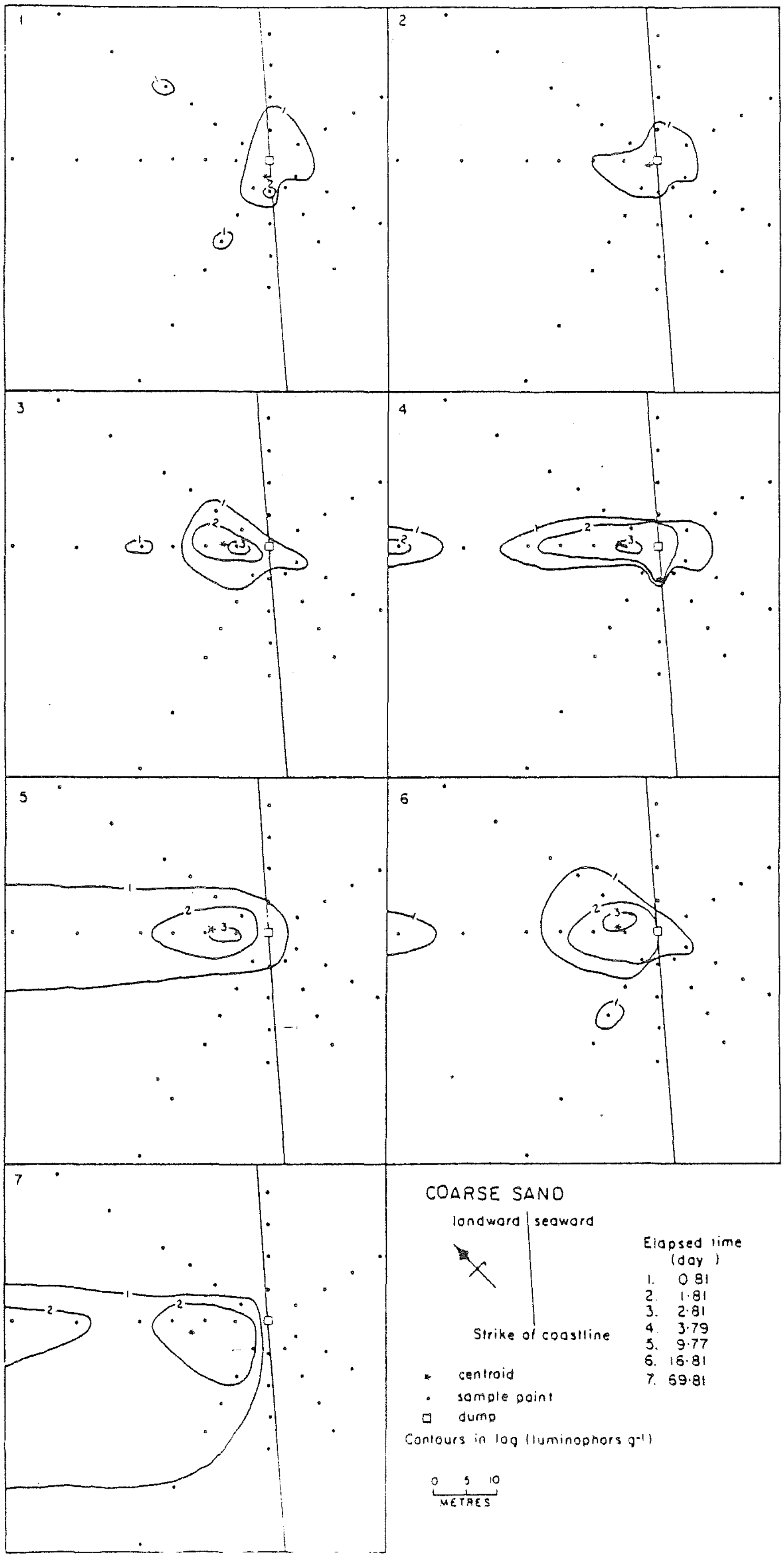


FIGURE 4.6 FLUORESCENT TRACER DISPERSION PATTERNS FOR COARSE SAND, EXPERIMENT 1.

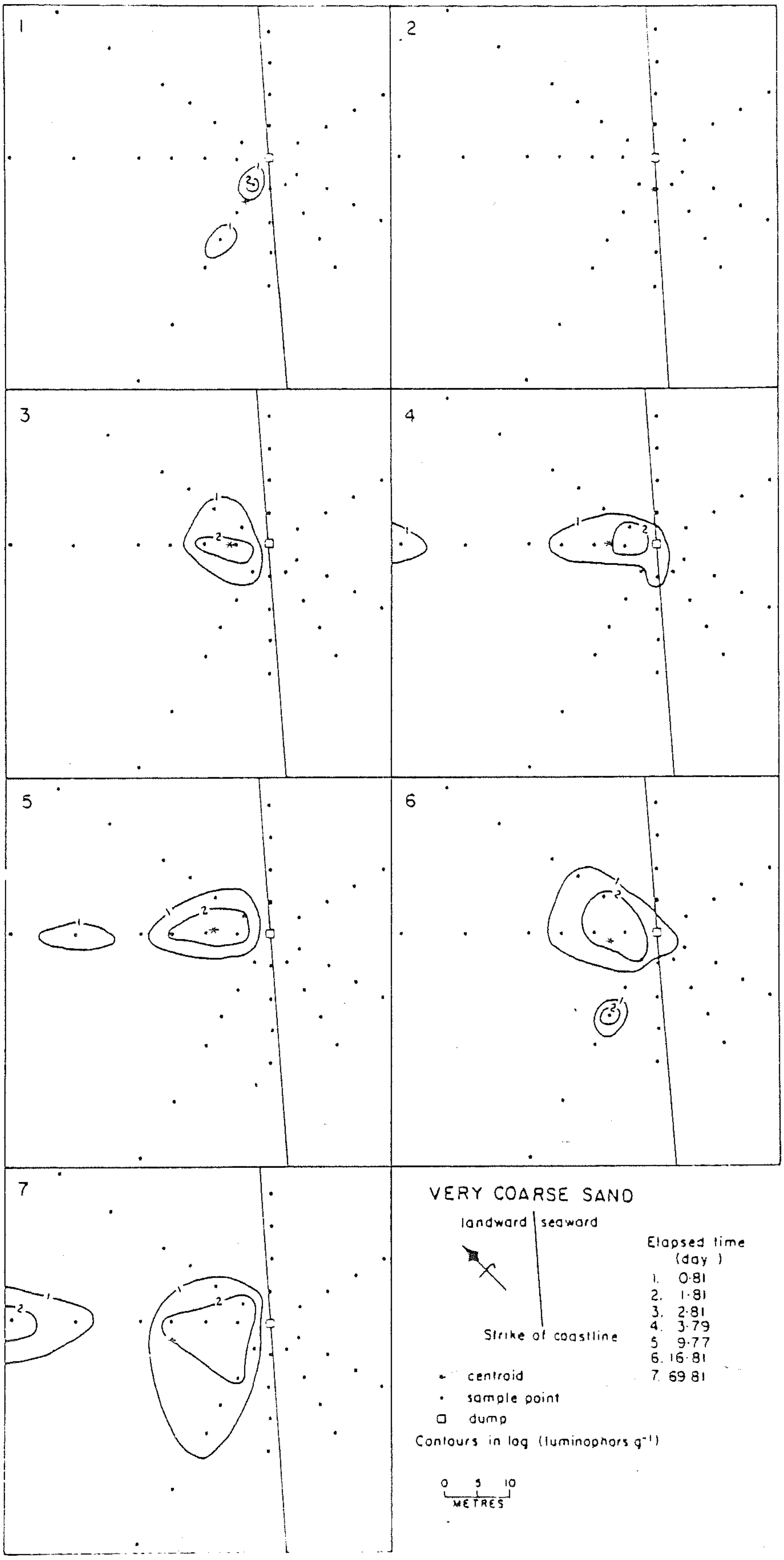


FIGURE 4.7 FLUORESCENT TRACER DISPERSION PATTERNS FOR VERY COARSE SAND, EXPERIMENT 1.

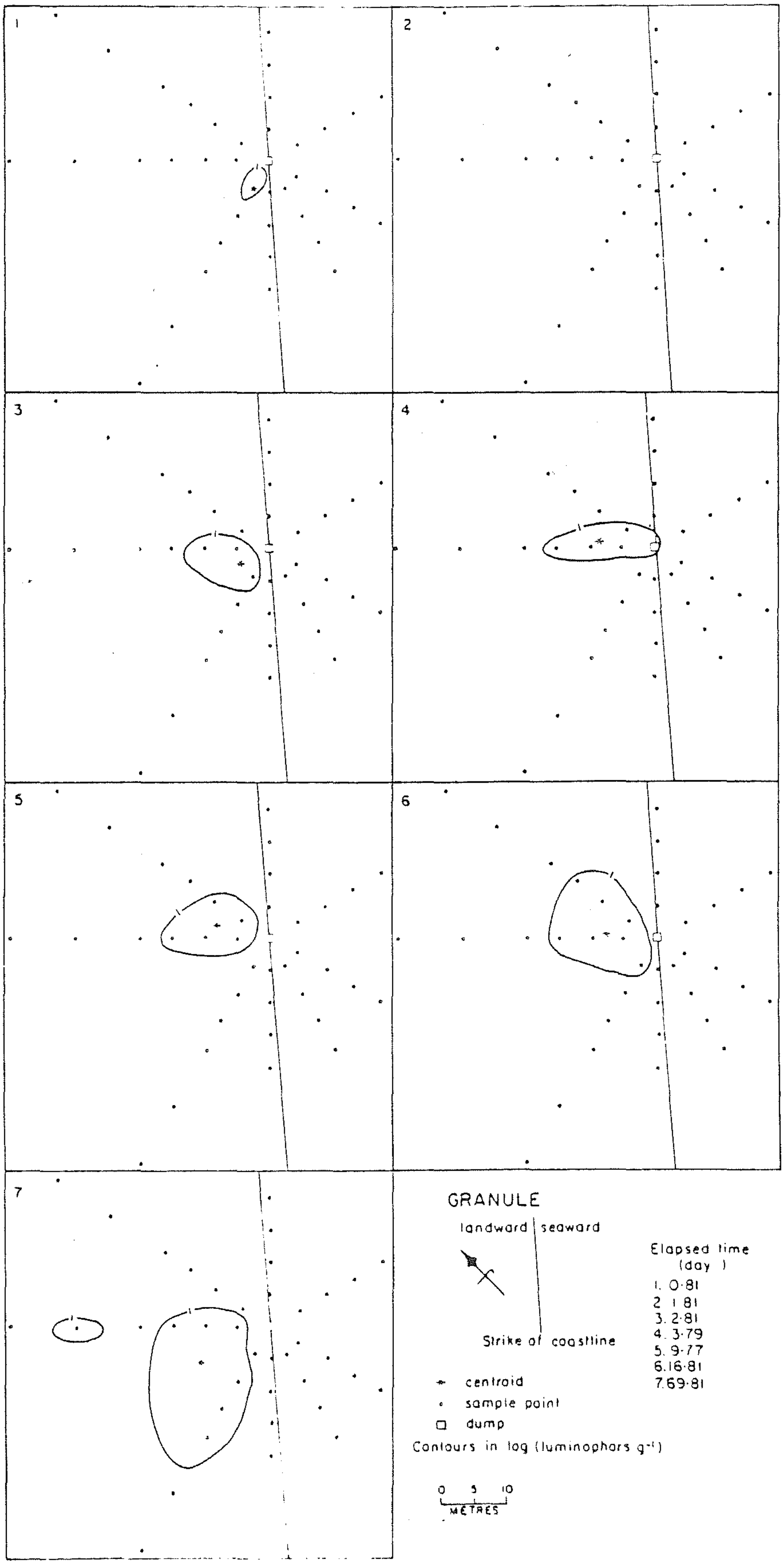


FIGURE 4.8 FLUORESCENT TRACER DISPERSION PATTERNS FOR GRANULES, EXPERIMENT 1.

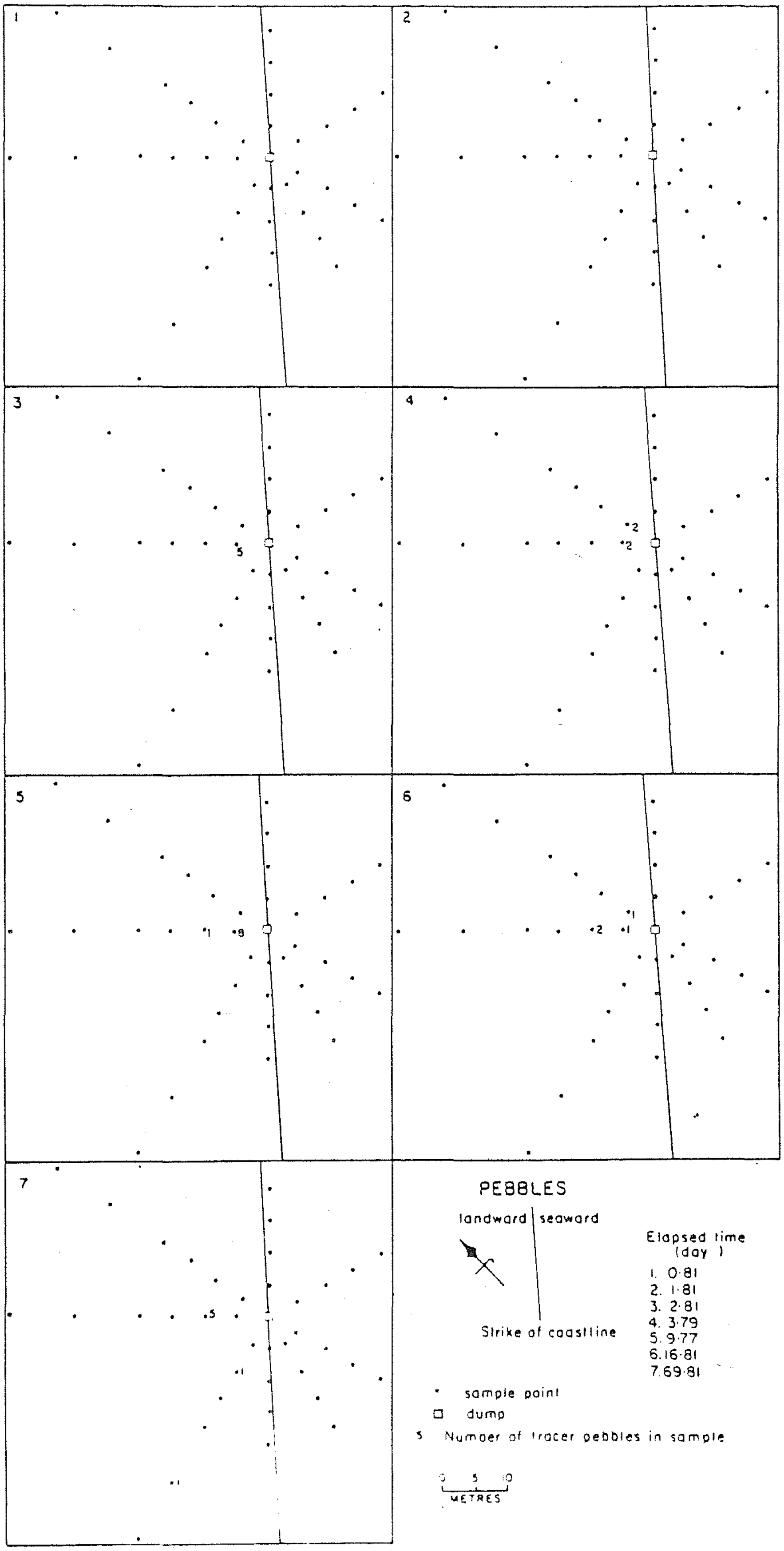


FIGURE 4.9 NUMBER OF FLUORESCENT TRACER PEBBLES FOUND AND THEIR LOCATION FOR EACH SAMPLE RUN, EXPERIMENT 1.

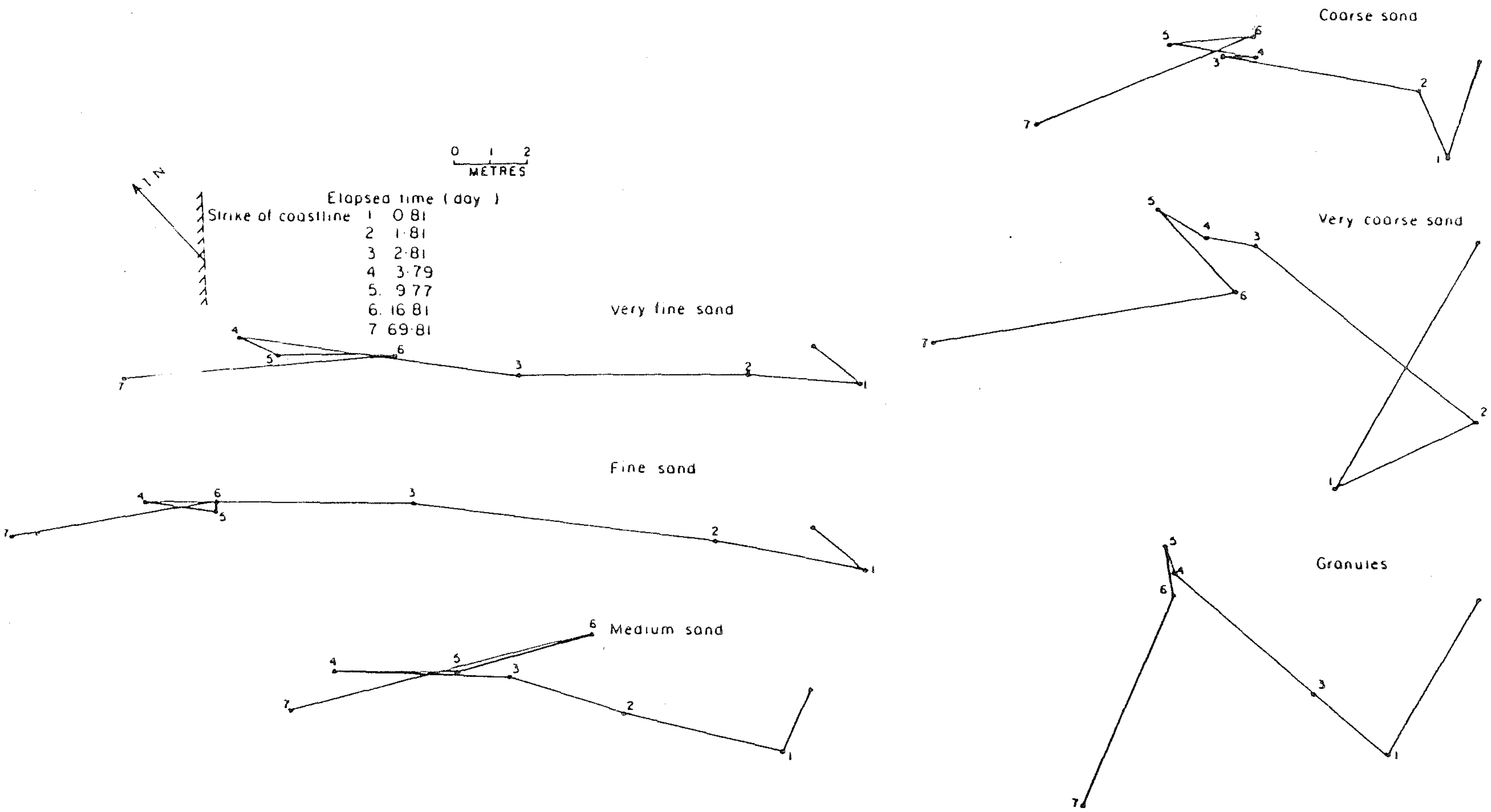


FIGURE 4.10 FLUORESCENT TRACER CENTROID MOVEMENT OVER TIME FOR VERY FINE SAND, FINE SAND, MEDIUM SAND, COARSE SAND, VERY COARSE SAND AND GRANULES, EXPERIMENT 1.

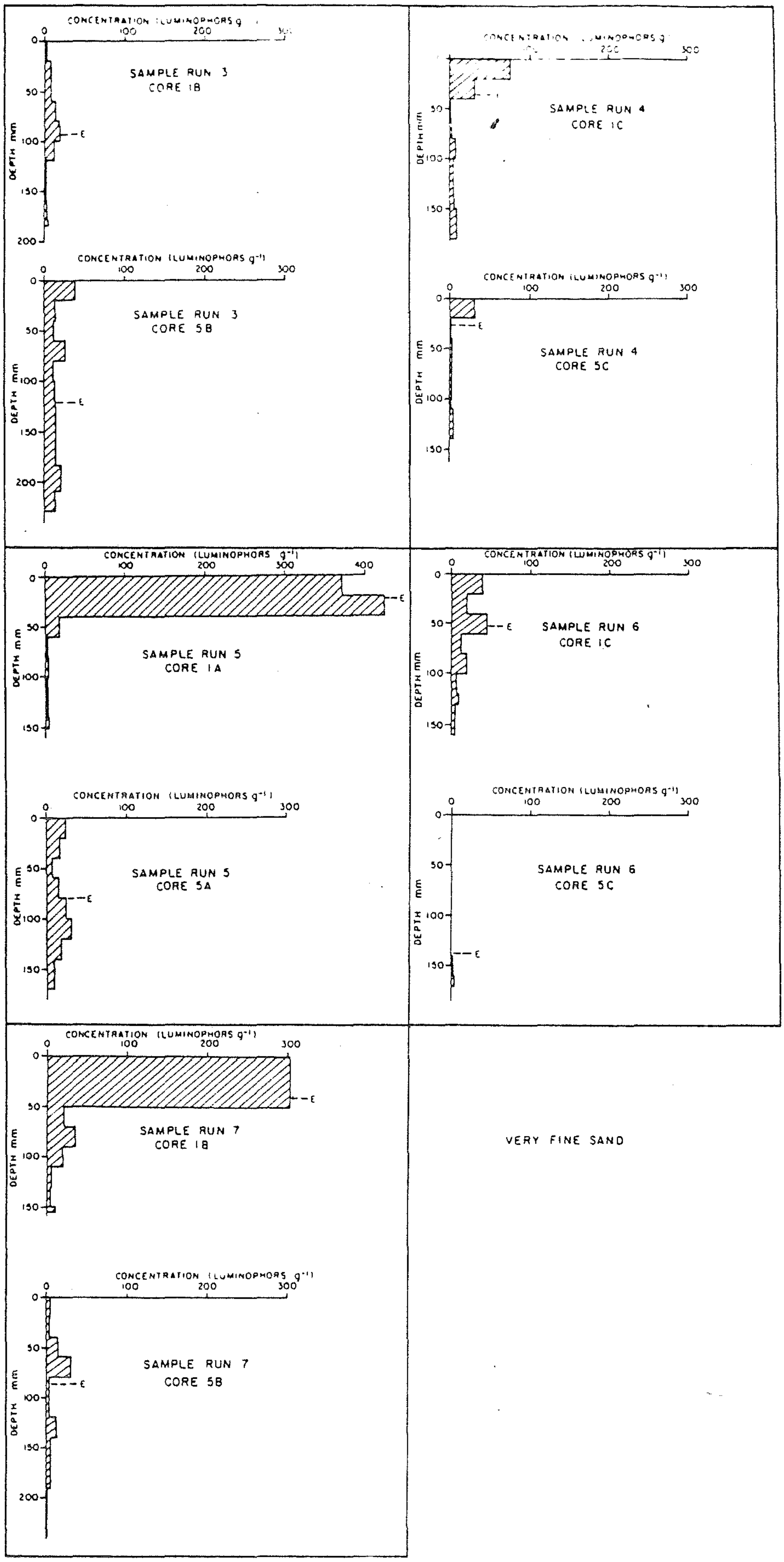


FIGURE 4.11 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, VERY FINE SAND, EXPERIMENT 1. THE CALCULATED THICKNESS OF THE MOBILE LAYER, E, IS INDICATED ON EACH DIAGRAM.

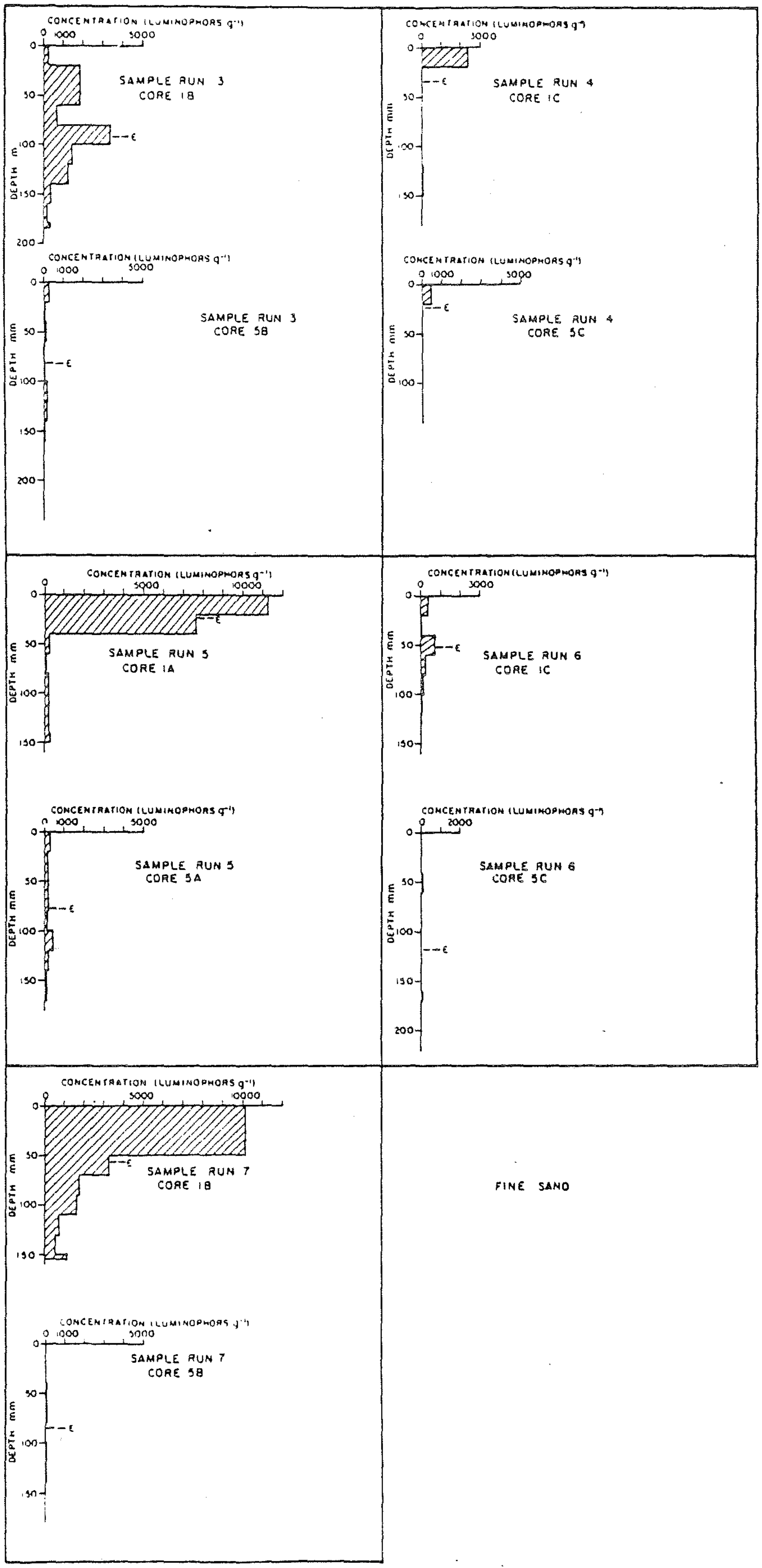


FIGURE 4.12 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, FINE SAND, EXPERIMENT 1. THE CALCULATED THICKNESS OF THE MOBILE LAYER, E, IS INDICATED ON EACH DIAGRAM.

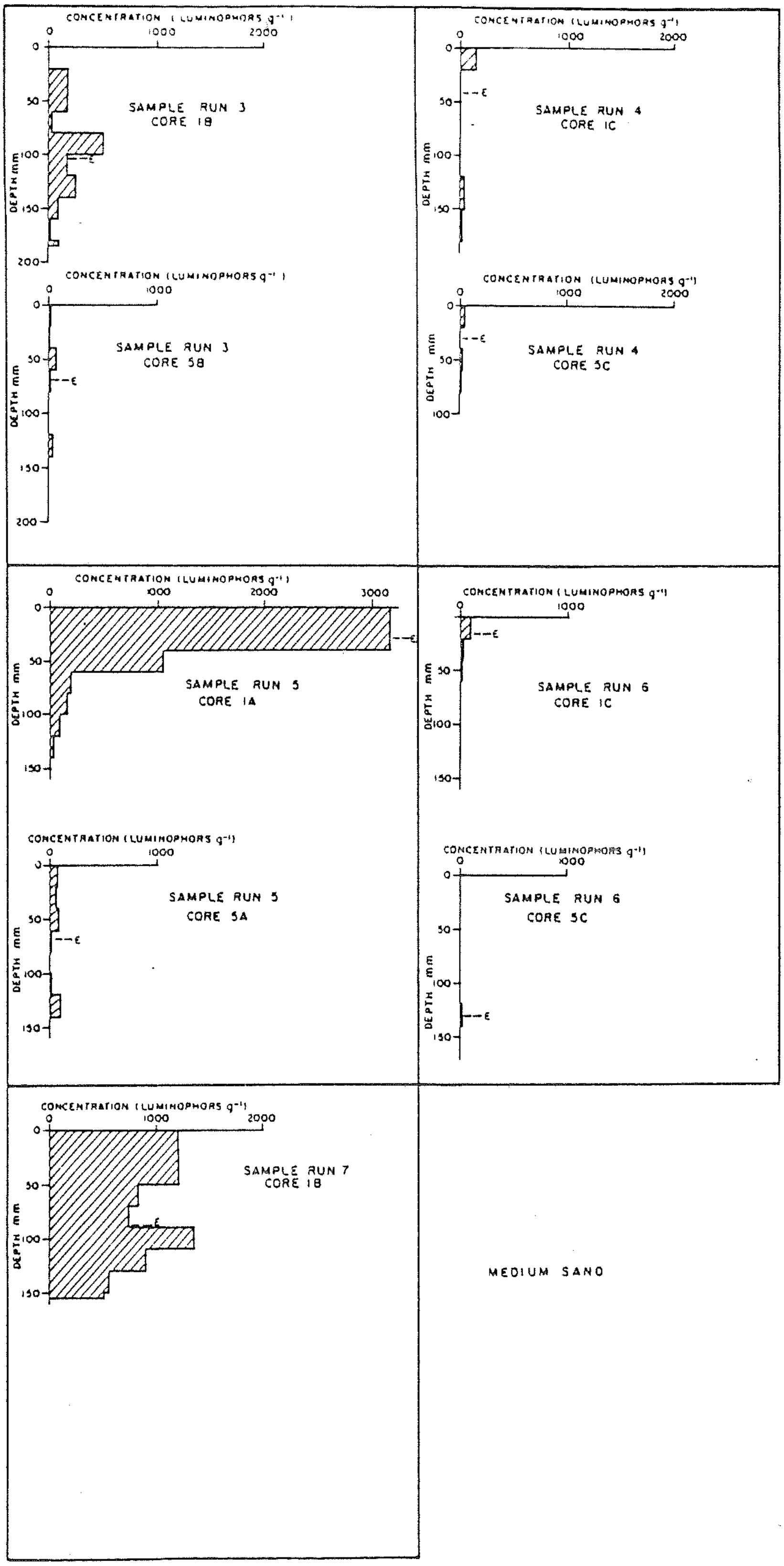


FIGURE 4.13 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, MEDIUM SAND, EXPERIMENT 1. THE CALCULATED THICKNESS OF THE MOBILE LAYER, E, IS INDICATED ON EACH DIAGRAM.

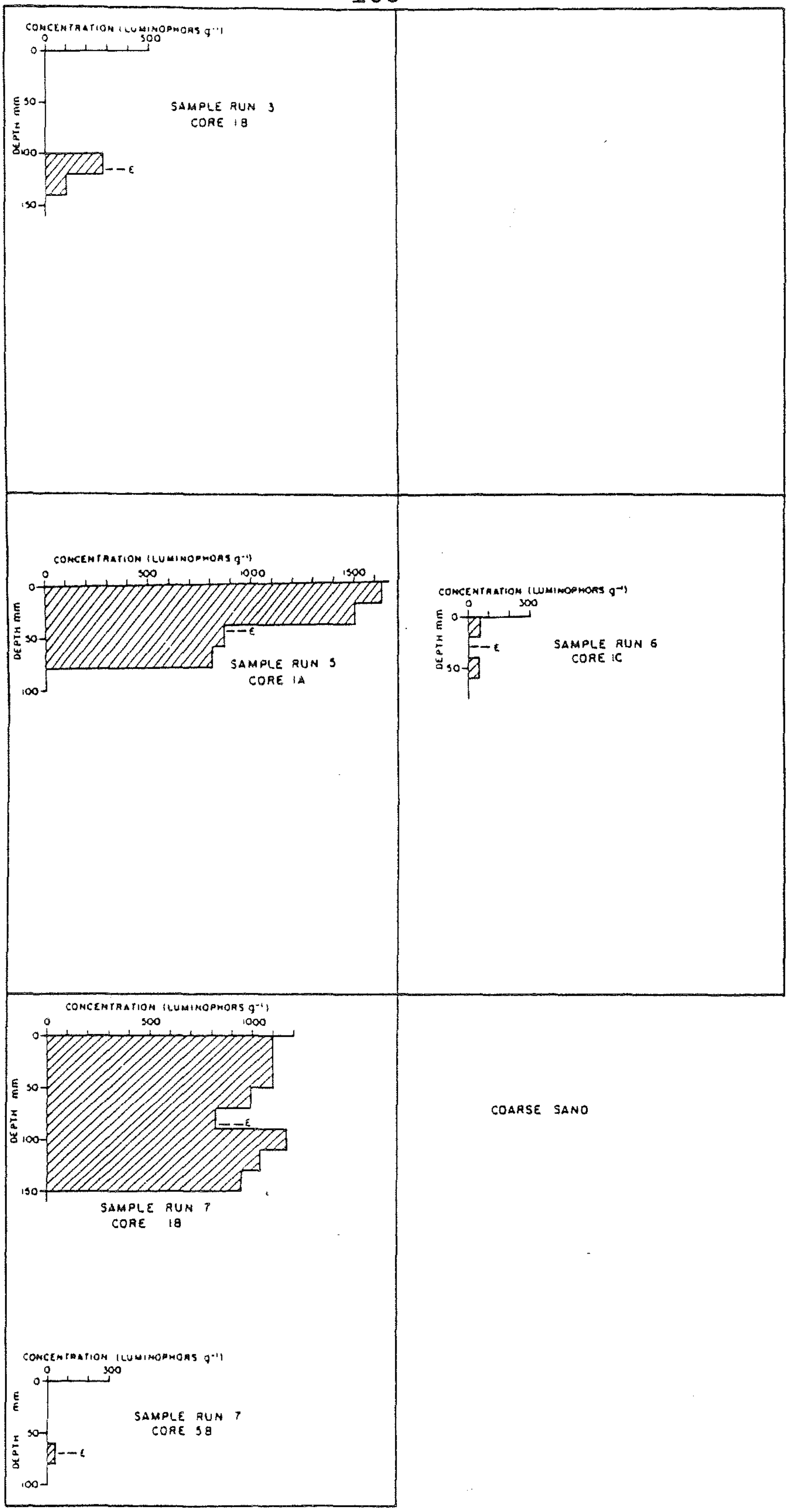


FIGURE 4.14 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, COARSE SAND, EXPERIMENT 1. THE CALCULATED THICKNESS OF THE MOBILE LAYER, E, IS INDICATED ON EACH DIAGRAM.

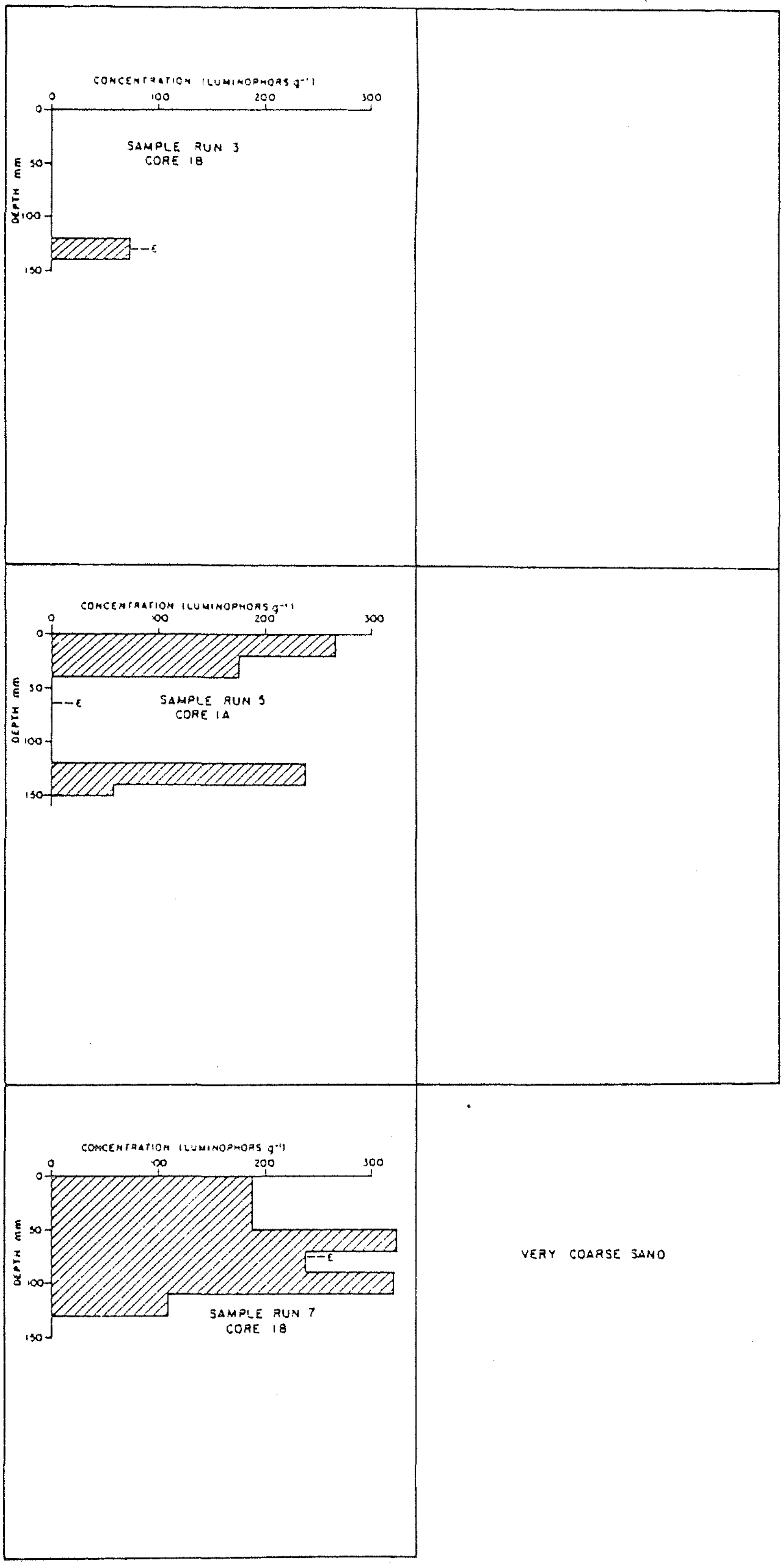


FIGURE 4.15 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, VERY COARSE SAND, EXPERIMENT 1. THE CALCULATED THICKNESS OF THE MOBILE LAYER, E, IS INDICATED ON EACH DIAGRAM.

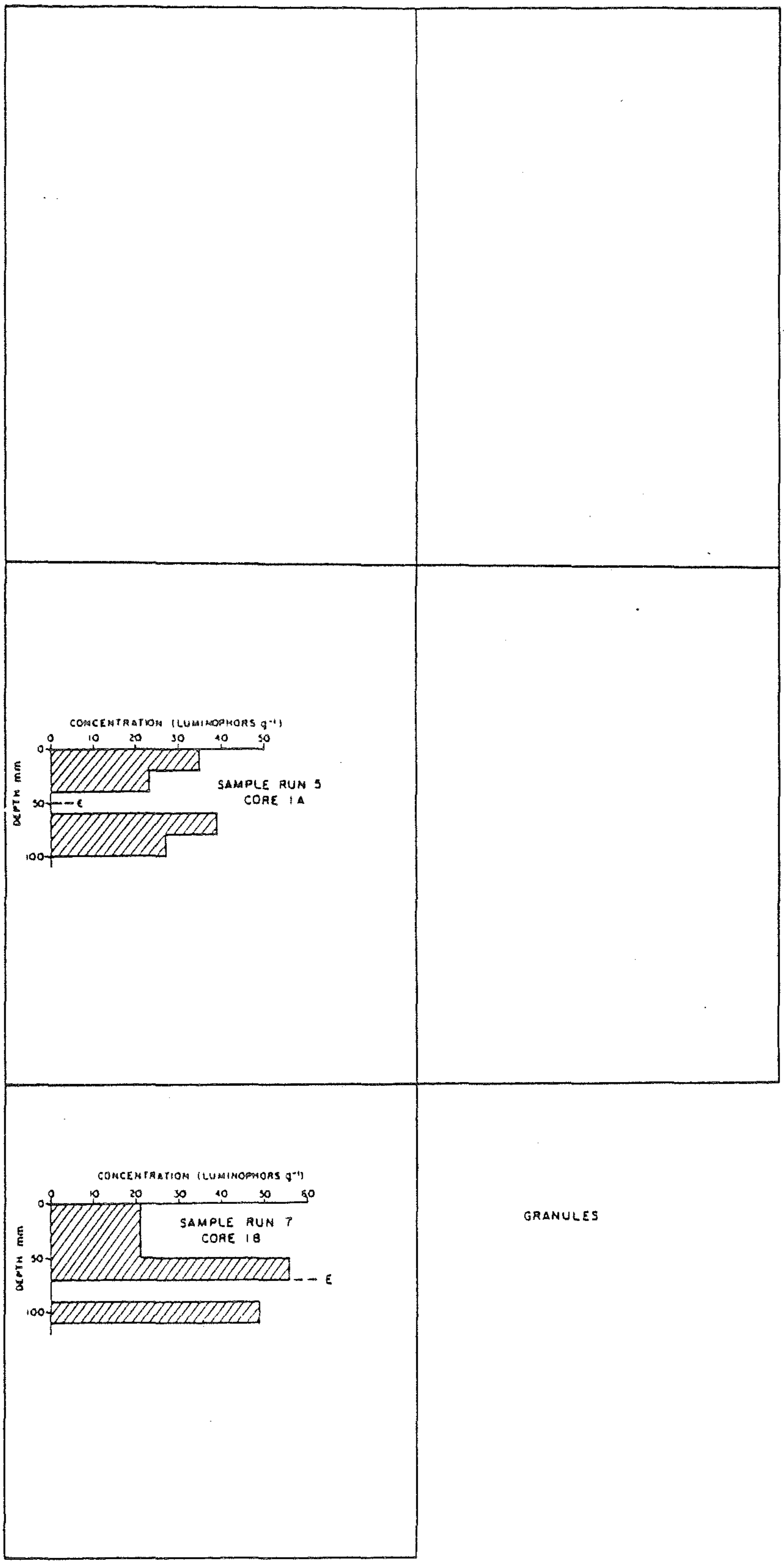


FIGURE 4.16 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, GRANULES, EXPERIMENT 1. THE CALCULATED THICKNESS OF THE MOBILE LAYER, E, IS INDICATED ON EACH DIAGRAM.

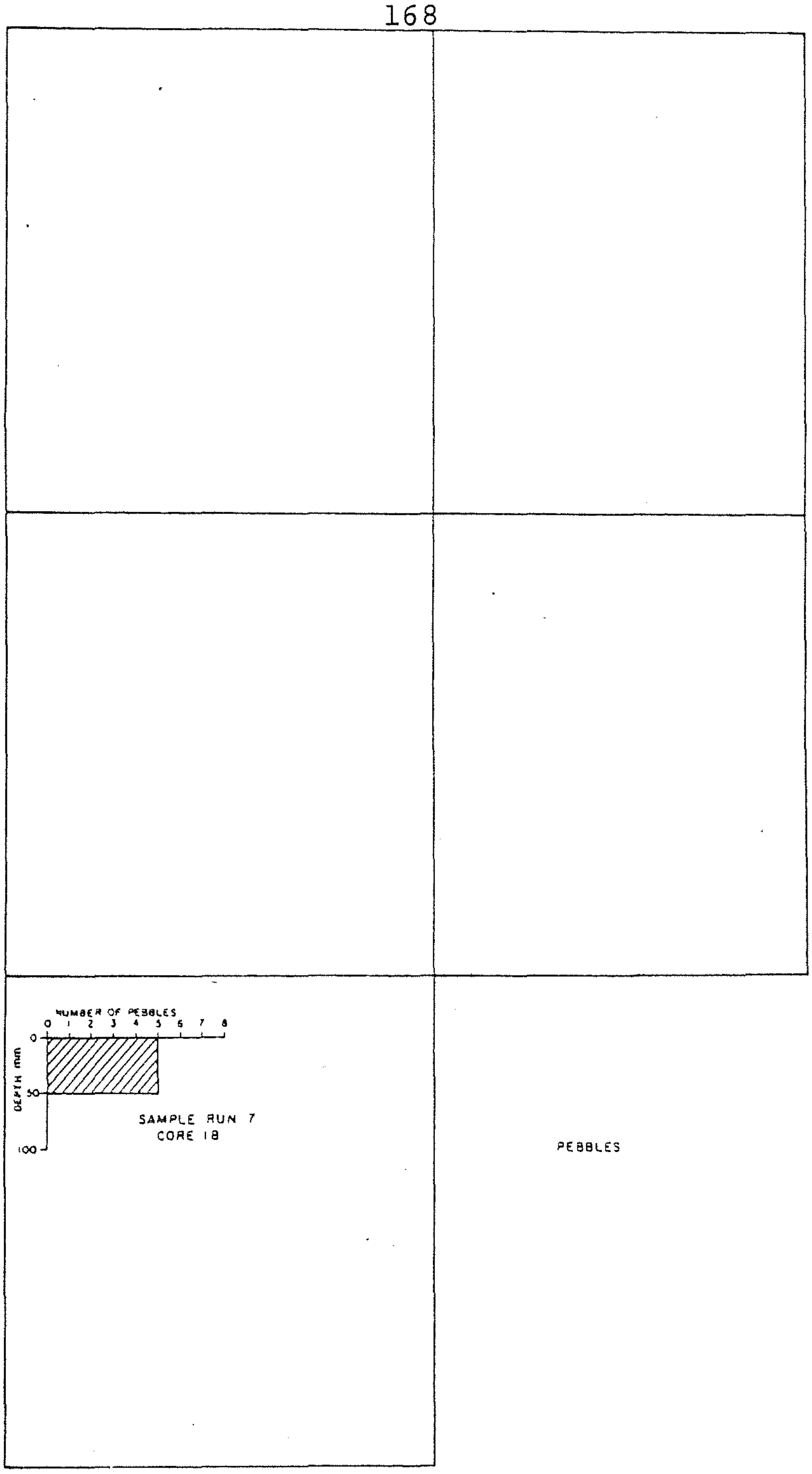


FIGURE 4.17 FLUORESCENT TRACER DISTRIBUTION WITH DEPTH, PEBBLES, EXPERIMENT 1.

medium sand, coarse sand, very coarse sand and granules respectively. Examination of these tables reveals that both the average grain velocity and the sediment transport rate decreased markedly after the first four sample runs. This decrease is to be expected because when the tracer was dumped it formed a mound on the seafloor which would have enhanced sediment transport. As time increased after dumping the tracer became incoporated into the entire mobile layer and the average grain velocity and the sediment transport rate were therefore reduced. Because of this decrease the results were divided into two groups - the first four sample runs and the final three sample runs - and numerical means of the average grain velocity and the sediment transport rate were calculated for each size class for each group. These numerical means, presented in table 4.10, represent a summary of the data in tables 4.4 - 4.9.

TABLE 4.4 VERY FINE SAND - TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	CENTROID DISPLACE-MENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	0.81	1.64	2.02	171	0.108	0.218
2	1.00	3.11	3.11	318	0.108	0.336
3	1.00	6.44	6.44	313	0.108	0.696
4	0.98	7.86	8.02	320	0.032	0.257
5	5.98	1.26	0.21	159	0.052	0.011
6	7.04	3.25	0.46	132	0.096	0.044
7	53.00	7.55	0.14	307	0.064	0.009

TABLE 4.5 FINE SAND - TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	CENTROID DISPLACE-MENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	0.81	1.89	2.33	172	0.087	0.203
2	1.00	4.29	4.29	324	0.087	0.373
3	1.00	8.41	8.41	320	0.087	0.732
4	0.98	7.52	7.67	313	0.029	0.223
5	5.98	2.01	0.34	141	0.050	0.017
6	7.04	0.36	0.05	43	0.085	0.004
7	53.00	5.83	0.11	303	0.071	0.008

TABLE 4.6 MEDIUM SAND - TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	CENTROID DISPLACE-MENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	0.81	1.93	2.38	249	0.087	0.207
2	1.00	4.47	4.47	331	0.087	0.389
3	1.00	3.35	3.35	334	0.087	0.291
4	0.98	4.91	5.01	319	0.036	0.180
5	5.98	3.42	0.57	139	0.053	0.030
6	7.04	3.98	0.57	117	0.074	0.042
7	53.00	8.69	0.16	299	0.069	0.011

TABLE 4.7 COARSE SAND - TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	CENTROID DISPLACE-MENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	0.81	2.83	3.49	242	0.115	0.402
2	1.00	2.05	2.05	23	0.115	0.236
3	1.00	5.50	5.50	323	0.115	0.633
4	0.98	0.85	0.87	139	0.115[1]	0.100
5	5.98	2.48	0.41	324	0.045	0.019
6	7.04	2.49	0.35	127	0.029	0.010
7	53.00	6.67	0.13	291	0.078	0.010

[1] There was no coarse sand in the cores from sample run 4. The value for sample run 3 was therefore used.

TABLE 4.8 VERY COARSE SAND - TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	DISPLACE-MENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	0.81	7.93	9.79	253	0.130	1.273
2	1.00	4.38	4.38	108	0.130	0.569
3	1.00	7.95	7.95	351	0.130	1.034
4	0.98	1.37	1.40	323	0.130[1]	0.182
5	5.98	1.54	0.26	346	0.064	0.016
6	7.04	3.13	0.44	178	0.064[1]	0.028
7	53.00	8.52	0.16	304	0.075	0.012

[1] There was no very coarse sand in the cores from sample runs 4 and 6. Values from sample runs 3 and 5 were therefore used.

TABLE 4.9 GRANULES - TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	CENTROID DISPLACE-MENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	0.81	4.97	6.14	253	0.050	0.307
2	1.00					
3	1.00	2.77	2.77	355	0.050[1]	0.139
4	0.98	5.04	5.14	351	0.050[1]	0.257
5	5.98	0.89	0.15	34	0.050	0.007
6	7.04	1.44	0.20	215	0.050[1]	0.010
7	53.00	6.39	0.12	247	0.070	0.008

[1] There were no granules in the cores from sample runs 3, 4 and 6. The value from sample run 5 was therefore used.

TABLE 4.10 NUMERICAL MEAN AVERAGE GRAIN VELOCITY AND NUMERICAL MEAN SEDIMENT TRANSPORT RATE FOR THE DATA DIVIDED INTO THE FIRST FOUR SAMPLE RUNS AND THE FINAL THREE SAMPLE RUNS.

SIZE CLASS	NUMERICAL MEAN AVERAGE GRAIN VELOCITY $m\ day^{-1}$		NUMERICAL MEAN SEDIMENT TRANSPORT RATE $m^3\ m^{-1}\ day^{-1}$	
	FIRST 4 SAMPLE RUNS	FINAL 3 SAMPLE RUNS	FIRST 4 SAMPLE RUNS	FINAL 3 SAMPLE RUNS
Very Fine Sand	4.90	0.27	0.377	0.021
Fine Sand	5.68	0.17	0.383	0.010
Medium Sand	3.80	0.43	0.267	0.028
Coarse Sand	2.98	0.30	0.343	0.013
Very Coarse Sand	5.88	0.29	0.765	0.019
Granules	4.68	0.16	0.234	0.008

For the first four sample runs the numerical mean of the average grain velocity ranged from 2.98 m day^{-1} for coarse sand to 5.88 m day^{-1} for very coarse sand. For the same time period the numerical mean sediment transport rate ranged from 0.234 m^3 m^{-1} day^{-1} for granules to 0.765 m^3 m^{-1} day^{-1} for very coarse sand. For the final three sample runs the numerical mean of the average grain velocity ranged from 0.16 m day^{-1} for granules to 0.43 m day^{-1} for medium sand. For the same time period the numerical mean transport rate ranged from 0.008 m^3 m^{-1} day for granules to 0.028 m^3 m^{-1} day^{-1} for medium sand. Possible reasons why average grain velocities and transport rates are at times higher for coarser sediments than for finer sediments are discussed in section 4.7.4.8.

The wave and wave-dependent parameters calculated for the period between each sample run are presented in table 4.11. For the duration of the experiment the average significant wave height was very close to or below 0.97 m, the average for the full set of wave data. Sample run 1 had the lowest wave conditions with an average significant height of 0.67 m and sample run 6 had the highest wave conditions with an average significant height of 1.02 m. Average significant wave period varied from 8 s for sample run 5 to 10 s for sample runs 2, 3 and 4. The average for the full set of data was 10 s. The average linear current, $\overline{U}_{max1}$, ranged from 33.5 cm s^{-1} for sample run 1 to 50.0 cm s^{-1} for sample 6. The linear current was sufficient to exceed the calculated threshold for very fine sand for 100% of the time throughout the whole experiment. At the other end of the scale the linear current was only sufficient to exceed the calculated value for pebbles for 9% of the time during sample run 5 and 2% of the time during sample run 6.

TABLE 4.11 WAVE AND WAVE-DEPENDENT PARAMETERS FOR THE PERIODS BETWEEN EACH SAMPLE RUN. FOR PARAMETER DEFINITIONS, SEE TABLE 4.3.

PARAMETER	SAMPLE RUN NUMBER						
	1	2	3	4	5	6	7
$\bar{H}_s$ (m)	0.67	0.79	0.98	0.95	0.88	1.02	0.76
$\bar{T}_s$ (s)	9	10	10	10	8	9	9
$(\bar{H}_s)^2$ (m^2)	0.45	0.62	0.96	0.90	0.77	1.04	0.58
$\bar{H}_{rms}$ (m)	0.50	0.59	0.74	0.71	0.64	0.74	0.55
$\bar{H}_{max}$ (m)	1.23	1.37	2.00	1.64	1.58	1.66	1.35
$\bar{U}_{max1}$ (cm s^{-1})	33.5	40.2	48.9	47.9	42.3	50.0	36.6
$\bar{U}_{max2}$ (cm s^{-1})	2.3	4.1	5.1	5.3	3.8	5.0	2.5
$\bar{U}_{max3}$ (cm s^{-1})	35.9	44.3	54.0	53.2	46.1	55.0	39.1
$\bar{U}_{max4}$ (cm s^{-1})	31.2	36.1	43.8	42.6	38.5	45.1	34.1
PER (%)							
very fine sand	100	100	100	100	100	100	100
fine sand	100	100	100	100	100	100	99
medium sand	100	100	100	100	100	100	92
coarse sand	90	92	100	100	85	98	70
very coarse sand	10	50	83	100	41	74	41
granules	0	0	17	25	17	40	10
pebbles	0	0	0	0	9	2	0

Because of the marked decrease in both the average grain velocity and the transport rate after the first four sample runs no linear relationships were found between these values and the wave and wave-dependent parameters in table 4.11. However, when the analysis was re-run using the data split into the two groups described previously some statistically significant linear relationships were found, despite the small number of data points. Tables 4.12 and 4.13 show the significant linear relationships found for very fine sand and fine sand respectively. The relationships were between the average grain velocity and wave and wave-dependent parameters for the first four sample runs only. Table 4.14 shows the one significant linear relationship that was found for medium sand. It was for the final three sample runs. No significant linear relationships were found for coarse sand but several were found for very coarse sand for the final three sample runs. The details of these relationships are given in table 4.15. For granules several significant relationships were found between the average grain velocity and the wave and wave-dependent parameters for the final three sample runs only. These relationships are presented in table 4.16.

The significant linear relationships that were found were all positive so that an increase in the wave or wave-dependent parameter will cause a proportionate increase in the average grain velocity and the sediment transport rate.

The results are discussed in greater detail in section 4.7.4.

TABLE 4.12 SIGNIFICANT LINEAR RELATIONSHIPS FOR VERY FINE SAND FOR THE FIRST FOUR SAMPLE RUNS, EXPERIMENT 1.

INDEPENDENT VARIABLE	DEPENDENT VARIABLE	r^2	SIGNIFICANCE LEVEL	INTERCEPT A	SLOPE B
$\overline{H}_s$	V[1]	0.87	0.05	-10.441	18.099
$(\overline{H}_s)^2$	V	0.88	0.05	-3.310	10.959
$\overline{H}_{rms}$	V	0.86	0.05	-9.989	23.443
$\overline{U}_{max1}$	V	0.87	0.05	-10.610	0.364
$\overline{U}_{max2}$	V	0.82	0.05	-3.113	1.907
$\overline{U}_{max3}$	V	0.87	0.05	-9.505	0.308
$\overline{U}_{max4}$	V	0.88	0.05	-12.162	0.444

[1] When used in regression analyses V refers to the magnitude of the average grain velocity only.

TABLE 4.13 SIGNIFICANT LINEAR RELATIONSHIPS FOR FINE SAND FOR THE FIRST FOUR SAMPLE RUNS, EXPERIMENT 1.

INDEPENDENT VARIABLE	DEPENDENT VARIABLE	r^2	SIGNIFICANCE LEVEL	INTERCEPT A	SLOPE B
$\overline{H}_s$	V	1.00	0.01	-11.042	19.726
$(\overline{H}_s)^2$	V	1.00	0.01	-3.072	11.941
$\overline{H}_{rms}$	V	0.90	0.05	-6.767	20.397
$\overline{H}_{max}$	V	0.88	0.05	-6.669	7.913
$\overline{U}_{max1}$	V	0.99	0.01	-11.140	0.394
$\overline{U}_{max2}$	V	0.89	0.05	-2.851	2.030
$\overline{U}_{max3}$	V	0.98	0.01	-9.898	0.333
$\overline{U}_{max4}$	V	1.00	0.01	-12.892	0.483

TABLE 4.14 SIGNIFICANT LINEAR RELATIONSHIP FOR MEDIUM SAND FOR THE FINAL THREE SAMPLE RUNS, EXPERIMENT 1.

INDEPENDENT VARIABLE	DEPENDENT VARIABLE	r^2	SIGNIFICANCE LEVEL	INTERCEPT A	SLOPE B
$\overline{U}_{max2}$	q	0.99	0.05	-0.020	0.013

TABLE 4.15 SIGNIFICANT LINEAR RELATIONSHIPS FOR VERY COARSE SAND FOR THE FINAL THREE SAMPLE RUNS, EXPERIMENT 1.

INDEPENDENT VARIABLE	DEPENDENT VARIABLE	r^2	SIGNIFICANCE LEVEL	INTERCEPT A	SLOPE B
$\overline{H}_s$	V	0.99	0.05	-0.673	1.083
$(\overline{H}_s)^2$	V	1.00	0.05	-0.201	0.613
$\overline{U}_{max1}$	V	0.99	0.05	-0.615	0.021
$\overline{U}_{max3}$	V	0.99	0.05	-0.543	0.018
$\overline{U}_{max4}$	V	1.00	0.05	-0.717	0.026
$\overline{H}_s$	q	1.00	0.05	-0.048	0.077
$(\overline{H}_s)^2$	q	0.99	0.05	-0.014	0.043
$\overline{H}_{rms}$	q	1.00	0.01	-0.048	0.105

TABLE 4.16 SIGNIFICANT LINEAR RELATIONSHIPS FOR GRANULES FOR THE FINAL THREE SAMPLE RUNS, EXPERIMENT1.

INDEPENDENT VARIABLE	DEPENDENT VARIABLE	r^2	SIGNIFICANCE LEVEL	INTERCEPT A	SLOPE B
$\bar{H}_s$	V	0.99	0.05	-0.117	0.309
$(\bar{H}_s)^2$	V	1.00	0.05	0.018	0.175
$\bar{H}_{rms}$	V	0.99	0.05	-0.115	0.423
$\bar{U}_{max1}$	V	1.00	0.05	-0.101	0.006
$\bar{U}_{max3}$	V	0.99	0.05	-0.080	0.005
$\bar{U}_{max4}$	V	1.00	0.05	-0.130	0.007

4.7.3 Additional Analysis

4.7.3.1 Rollability Analysis Of Coarse Sand

Rollability, a functional measure of sand-grain shape, was used to try and distinguish differences between tracer particles of the same size that had moved different distances. The rollability apparatus used for the tests is composed of a smooth-walled, inclined cylinder. The sample to be analysed is placed in the upper end of the cylinder which is then rotated. The grains roll and slide down the length of the cylinder and then fall down a chute onto a micro-balance with an electrical output. This enables the median rolling time for the sample to be determined. Relatively more angular grains are pulled higher up the wall of the cylinder before rolling or sliding back down to the main axis. They therefore travel a greater distance in the cylinder and hence have relatively longer rolling times compared with more spherical grains.

Tests were carried out only on grains in the coarse sand size class for two reasons. Firstly, it was not possible to keep sieve meshes smaller than 0.5 mm absolutely clean and hence ensure that there was no contamination between samples. Secondly, the number of individual tracer grains recovered in the coarser size classes was insufficient for the analysis. The analysis of coarse sand was limited to sample runs 5 and 7 because it was desirable to keep the number of grains as high as possible.

Initially it was hoped that individual grains could be used for the analysis but preliminary tests revealed that no repeatability could be achieved and so this method was not used. Instead, the following procedure was employed:

1. Samples of coarse sand on the same grid line were chosen.

2. The samples were sieved to ¼ ϕ intervals using sieves that were cleaned after each sample.

3. For each size fraction the smallest sample was chosen and the tracer grains (excluding any shell) were picked out using a pair of tweezers. The grains were then counted. For the remaining samples of that size fraction tracer grains were again picked out and then split using a micro-sample splitter to give approximately the same number of individual grains as the smallest sample.

4. The samples of tracer grains were weighed and the average grain weight calculated.

5. Each sample was run through the rollability apparatus twice and the median rolling time for each run determined. These times were averaged to give an average median rolling time for each sample.

The results of the analysis are presented in table 4.17. Generally, good repeatability was obtained from the rolling process with the exception of one 0.850 mm sample. No consistent trends occurred either with respect to the average individual grain weight or with respect to median rolling time.

4.7.3.2 Index Of Net Movement

Most of the dispersion patterns shown in figures 4.3 - 4.8 show a dominant landward movement of tracer grains. In order to quantify this observation an index of net movement, as defined by Murray (1967), was calculated for each dispersion pattern. The index is defined as follows:

$$\theta = \sum_{i=1}^{n} A_{il} c_i \Big/ \sum_{i=1}^{n} A_i c_i \qquad 4.5$$

where θ = index of net movement

A_i = the total area contained by the i th contour

A_{il} = that component of the total area landward of a line drawn through the grain source and parallel to the coast

c_i = the concentration value of the i th contour ($c_1 = 10$, $c_2 = 100$, $c_3 = 1000$ ... because contours were drawn on a logarithmic basis)

n = the number of contours present

TABLE 4.17 RESULTS OF ROLLABILITY ANALYSIS OF COARSE SAND, EXPERIMENT 1.

SAMPLE RUN NUMBER	SIZE (mm)	DISTANCE MOVED (m)	WEIGHT (g)	NO. GRAINS	AVERAGE GRAIN WEIGHT (10^{-3}g)	MEDIAN ROLLING TIMES (s)		AVERAGE MEDIAN ROLLING TIME (s)
5	0.850	5	0.1025	73	1.404	21.4	23.5	22.5
5	0.850	10	0.0982	70	1.403	21.9	21.8	21.9
7	0.850	5	0.2418	170	1.422	22.1	23.4	22.8
7	0.850	10	0.3183	220	1.447	22.5	21.0	21.8
7	0.850	15	0.3236	230	1.407	21.9	21.8	21.9
5	0.710	5	0.0885	95	0.9316	23.3	23.2	23.3
5	0.710	10	0.0594	67	0.8866	24.5	24.0	24.3
7	0.710	5	0.1632	184	0.8869	23.0	23.1	23.1
7	0.710	10	0.1606	180	0.8922	22.8	22.1	22.5
7	0.710	15	0.1533	181	0.8469	22.3	22.1	22.2
5	0.600	5	0.0972	170	0.5718	24.0	24.5	24.3
5	0.600	10	0.0956	175	0.5463	24.0	24.5	24.3
7	0.600	5	0.1363	248	0.5495	24.0	24.8	24.4
7	0.600	10	0.1419	263	0.5395	25.4	23.5	24.5
7	0.600	15	0.1391	251	0.5541	25.3	25.0	25.2
5	0.500	5	0.0283	80	0.3538	25.7	25.7	25.7
5	0.500	10	0.0279	80	0.3488	26.8	27.0	26.9
7	0.500	5	0.0687	206	0.3334	24.0	25.0	24.5
7	0.500	10	0.0690	211	0.3270	24.1	24.1	24.1
7	0.500	15	0.0614	192	0.3197	24.0	23.9	24.0

The index θ is the ratio of the sum of weighted landward areas enclosed by the contours to the sum of weighted total areas enclosed by the contours. The index can vary between 0 and 1. If all grain movement is landward θ = 1 and if all grain movement is seaward θ = 0. Values of θ between 0 and 0.5 indicate a net movement of grains in a seaward direction and values of θ between 0.5 and 1.0 indicate a net movement of grains in a landward direction. Increasing values of θ indicate an increasing tendency for grains to move in a landward direction.

Table 4.18 presents the calculated θ values for each dispersion pattern and gives an average for each size class. Figure 4.18 shows the relationship between θ and grain size. The relationship was tested with regression analysis and was found to be statistically significant at the 5 percent level. The line of best fit determined from the regression is drawn on the diagram.

TABLE 4.18 INDEX OF NET MOVEMENT FOR VERY FINE SAND, FINE SAND, MEDIUM SAND, COARSE SAND, VERY COARSE SAND AND GRANULES, EXPERIMENT 1.

SAMPLE RUN NUMBER	VERY FINE SAND	FINE SAND	MEDIUM SAND	COARSE SAND	VERY COARSE SAND	GRANULES
1	0.49	0.44	0.47	0.51	1.00	
2	0.62	0.79	0.85	0.56		
3	0.91	0.96	0.99	0.98	1.00	1.00
4	0.93	0.97	0.97	0.89	0.90	0.98
5	0.87	0.97	0.99	0.99	1.00	1.00
6	0.97	0.92	0.96	0.99	0.99	1.00
7	0.99	0.98	1.00	1.00	1.00	1.00
Average	0.83	0.86	0.89	0.85	0.98	1.00

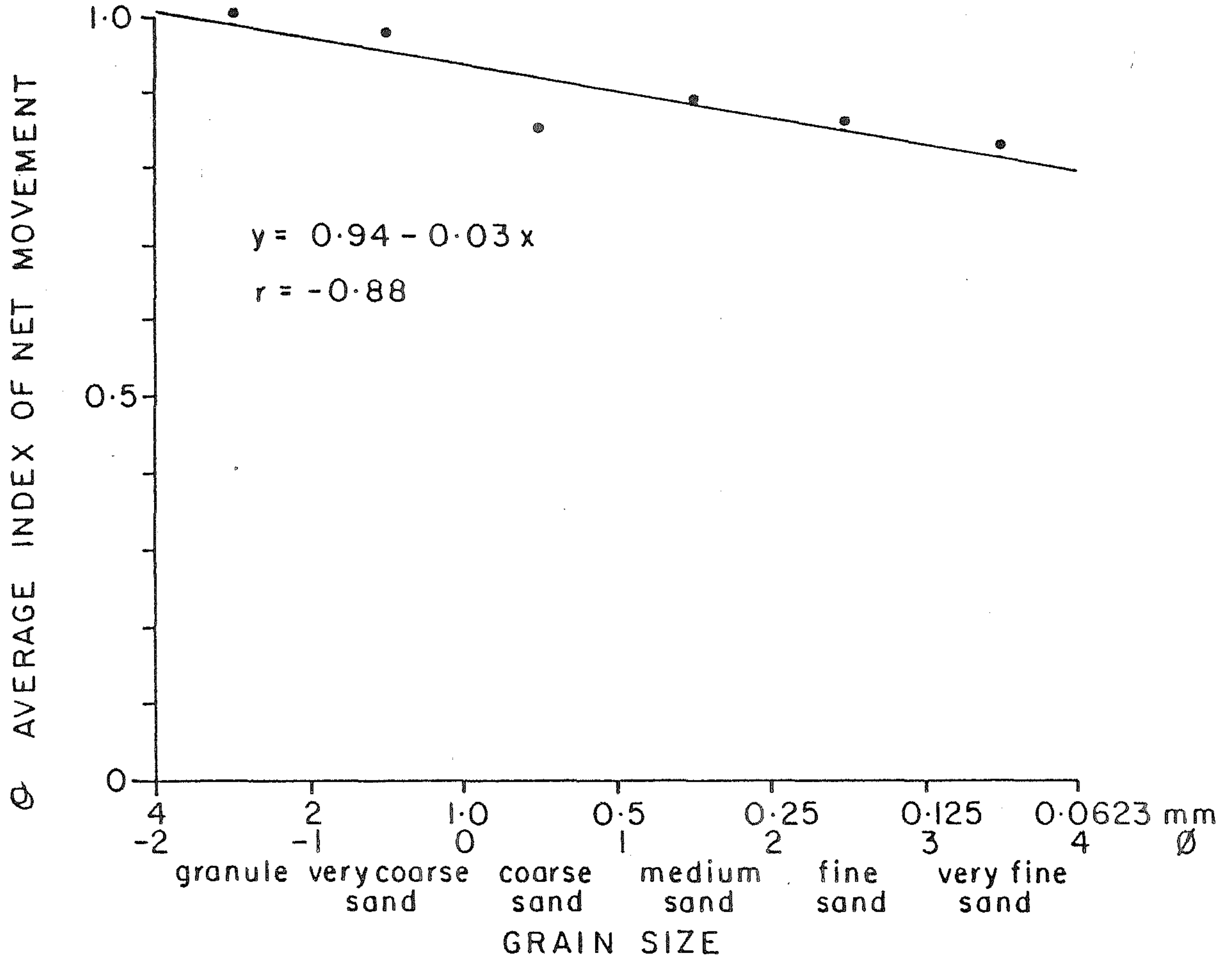


FIGURE 4.18 RELATIONSHIP BETWEEN AVERAGE INDEX OF NET MOVEMENT, θ, AND GRAIN SIZE FOR EXPERIMENT 1. THE LINEAR REGRESSION IS SIGNIFICANT AT THE 5% LEVEL.

All size classes indicate a net landward movement with an increasing tendency for landward movement with increasing grain size.

4.7.3.3 Tracer Accounting

One requirement of a tracer study is that all of the tracer grains released can be accounted for. The amount of tracer accounted for in the present study was difficult to determine because of the wide size range and because the tracer concentrations were expressed as luminophors g^{-1} and not as the total number of luminophors in a sample. However, some estimates were made.

For very fine sand, fine sand, medium sand, coarse sand and very coarse sand the first step was to determine the number of grains per gram. The reason for this is that detection involved counting individual grains, rather than weighing them, whereas the initial amounts released were weighed. To calculate the number of grains per gram, Ng, the following formula was used:

$$Ng = \text{mass} / (\text{volume} \times \text{density}) \qquad 4.6$$

Assuming that the grains are spherical then:

$$\text{Volume} = 4/3\ \pi r^3 \qquad 4.7$$

Therefore taking a mass of 1.0 g:

$$Ng = 1 / (4/3\ \pi r^3 \rho_b) \qquad 4.8$$

where r = radius of grains (cm)
ρ_b = bulk density of grains ($g\ cm^{-3}$)

Bulk density was taken as 1.75 g cm^{-3}, the value given by Terzaghi and Peck (1968, table 6.3, p. 28) for uniform dense dry sand. A median radius was taken for each size class. For example, very fine sand has a median diameter of 3.5 ϕ (0.884 mm) so the median radius was taken as 0.00442 cm. Table 4.19 shows the number of grains per gram that were calculated for very fine sand, medium sand, coarse sand and very coarse sand.

TABLE 4.19 NUMBER OF GRAINS PER GRAM FOR VERY FINE SAND, FINE SAND, MEDIUM SAND, COARSE SAND AND VERY COARSE SAND. CALCULATED FROM EQUATION 4.8 USING A MEDIAN RADIUS FOR EACH SIZE CLASS.

SIZE CLASS	GRAINS PER GRAM
very fine sand	1.59×10^6
fine sand	1.98×10^5
medium sand	2.48×10^4
coarse sand	3.10×10^3
very coarse sand	3.88×10^2

For very fine sand the number of grains per gram was also calculated by three additional techniques. The first additional technique used equation 4.8 but, instead of taking a median size, information from a sieved sample of very fine tracer sand was used to work out the number of grains for each sieve fraction, assuming the grain size for each ¼ ϕ was intermediate between the mesh sizes. These numbers were then weighted by the relative percentage of the sample retained on each sieve and summed to give the total number of grains in the sample. This yielded a value of 9.1×10^5 grains per gram. The second additional technique again used equation 4.8 but this time the input was the mean grain size determined from the sieved sample. This produced a value of 7.5×10^5 grains per gram. For the third additional technique, 1.0000 g of dyed sand was mixed with 99.0000 g of undyed sand. This mixture was then repeatedly split using a micro-sample splitter until an amount suitable for counting remained. The subsample was weighed, placed on a sheet of paper and taken into a dark room where the luminophors present were counted with the aid of a UV light. The number of dyed grains per gram was then calculated and multiplied by 99 to give the total number of grains in the subsample. The splitting and counting process was repeated five times and an average number of grains per gram determined. The resulting value was 3.6×10^5 grains per gram.

The next step in the accounting process was to determine the ratio of the total area sampled, A_s, to the total area covered by the grid, A. Because the grid was approximately 60 m x 60 m A was taken to be 3600 m^2. The total area sampled, A_s, was determined from:

$$A_s = n\, a_s \tag{4.9}$$

where n = number of samples = 38

a_s = area of one sample = 0.00916 m^2.

Therefore $A_s = 0.3481\ m^2$ and the ratio A_s:A equalled 1:10342.

Information from the sediment survey showed that in each sample the approximate percentages of very fine sand, fine sand and medium sand were 0.9, 0.03 and 0.006 respectively. Therefore by using these values and the total sample weight it was possible to calculate an approximate weight of very fine sand, fine sand and medium sand occurring in each tracer sample. The total number of grains in each of these size classes occurring during each sampling run, N_t, was then calculated from:

$$N_t = \sum_{i=1}^{n} w_i \, c_i \qquad 4.10$$

where w_i = calculated weight in size class for sample i (g)

c_i = concentration of tracer grains in size class for sample i (luminophors g^{-1})

n = number of samples

The values of N_t can then be converted to weights by using the figures in table 4.19 and multiplied by 10342 to give the total weight that can be accounted for in each sampling run.

For coarse sand and very coarse sand the weight of tracer that could be accounted for, W, was calculated from:

$$W = \left(\sum_{i=1}^{n} M_i \right) 10342/Ng \qquad 4.11$$

where M_i = number of tracer grains in sample i

N_g = number of grains per gram

n = number of samples

If an individual sample had been split before counting M_i was taken as 2^k, where k is the number of splits.

For granules and pebbles the weight of the tracer particles that were recovered was recorded. The amount of tracer that could be accounted for was then calculated from:

$$W = \sum_{i=1}^{n} w_i \quad 10342 \qquad 4.12$$

where w_i = weight of granules/pebbles in the i th sample (g)

n = number of samples

Table 4.20 shows the calculated percentage of tracer accounted for each size class for each sample run. Four figures are given for very fine sand because of the four methods used to calculate the number of grains per gram.

TABLE 4.20 PERCENTAGES OF TRACER ACCOUNTED FOR, EXPERIMENT 1.

SAMPLE RUN	VERY FINE SAND TECHNIQUE [1] 1	2	3	4	FINE SAND	MEDIUM SAND	COARSE SAND	VERY COARSE SAND	GRANULES	PEBBLES
1	10	17	21	44	12	2	1	1	0	0
2	21	37	45	94	32	15	1	0	0	0
3	31	54	65	136	69	43	10	15	61	28
4	29	51	62	128	90	74	17	15	19	11
5	15	26	32	67	44	53	32	32	85	76
6	7	12	14	29	22	42	20	19	47	140
7	5	8	10	20	13	42	54	51	83	125

[1] Technique 1 used equation 4.8 and the median radius for the very fine sand size class. Technique 2 used equation 4.8 and data from each fraction of a sieved sample. Technique 3 used equation 4.8 and the mean grain size for the sieved sample and technique 4 used counting of known dilutions to determine the number of grain per gram.

4.7.4 Discussion

4.7.4.1 Size Classes

When the amount of tracer material produced in each size class was determined no information was obtained about the grain size distribution within each size class. The only size class where the distribution was known was very fine sand which was essentially obtained only from Caroline Bay.

During the experiment all size classes were treated as though they had each been used in a separate experiment. No attempt was made to standardise the number of particles released in each size class. Therefore the concentration values presented are not directly comparable between size classes.

4.7.4.2 Dispersion Patterns

The dispersion patterns shown in figures 4.3 - 4.8 show that there was a dominant landward movement for all grain sizes. For the pebble size class the movement as shown in figure 4.9 was also landward and no pebbles were recovered on the seaward side of the grid. The fact that no pebbles were found in the grid sample taken at sample point 1B on sample run 7 but that five pebbles were found in the core taken at the same site highlights the sampling problems for the coarser size classes. The number of individual tracer particles released in these size classes was many orders of magnitude smaller than the number of individual particles released in the finer size classes. In situ detection of individual particles, as is possible with radioactive tracers, would have been a definite advantage for the coarser size classes.

The fact that most of the dispersion patterns for very fine sand, fine sand, medium sand and some for coarse sand and very coarse sand have open contours results from tracer material moving outside the sampling area. It would have been desirable to sample over a larger area and hence ensure that the total area over which the tracer was moving was sampled. To achieve this one of the alternative position fixing methods would have been required. However, the rope grid would still have been necessary for accurate sample positioning around the dump site which was particularly important for the coarser sized material. Therefore when tracing such a wide size range of sediment simultaneously using fluorescent tracers a combination of position fixing methods may be advantageous.

Many of the dispersion patterns for very fine sand, fine sand, medium sand, coarse sand and very coarse sand show an increase in tracer concentration at sample points 1E and 1F. During the sampling it was found that sample tubes could only be driven in about 10 cm at these points, due to the thin sediment cover, and hence a relatively small sample volume was obtained. If samples were taken deeper than the depth of tracer mixing concentrations (luminophors g^{-1}) would be reduced in proportion to the total volume of sediment and this is probably why 1E and 1F have higher concentration values. If the concentrations were expressed as the total number of grains in a sample this problem would not arise. However, for this to have been done the relative percentage of each size class in each sample would have been required. To obtain this information the analysis procedure would have required that all samples and subsamples were weighed prior to any sample splitting so that relative percentages of the sieved fractions could have been converted to a total amount of that fraction present in the whole sample. This was not considered necessary at the time of analysis but on reflection it could have been useful in eliminating the type of problem outlined above and would have assisted in assessing the amount of tracer that could be accounted for.

4.7.4.3 Centroid Movement

The plots of the centroid movements over time shown in figure 4.10 also show the dominant landward movement of tracer material, although there are periods when centroids moved in a seaward direction. The maximum displacement of any centroid from the dump site was 22.3 m which falls well within the sampling area. Because there was a predominant landward movement of tracer material it is probable that if samples had been taken over a larger area the centroids would have been displaced a slightly greater distance in the direction of movement.

4.7.4.4 Tracer Distribution With Depth

The histogram plots of tracer concentration with depth shown in figures 4.11 - 4.17 show that the distribution is quite variable. The concentration in a particular core is obviously a function of where that core was taken. Many of the coarser sediments were found only in cores taken on the landward side of the grid and with the exception of the very fine sand cores for sample run 3 all cores on the landward side of the grid had greater concentrations of tracer than those on the seaward side of the grid. More cores should have been taken because two cores probably do not adequately describe the depth of mixing over the entire sampling area. It would have been useful to know the general movement of tracer throughout the experiment so that sampling and core collection could have been adjusted accordingly. In subsequent seafloor tracing experiments the core information was improved greatly by obtaining the depth of mixing from all samples and by improvements in the core tubes used for sampling.

4.7.4.5 Comparison Of Results With Other Studies

There are few published transport rates with which to compare those derived from this experiment. No transport rates were found for coarse sand, very coarse sand or granules and therefore no comparison is possible for these size classes.

Kirk (1978) carried out a fluorescent sand tracing experiment on the seafloor at Timaru, approximately 600 m to the north-east of the site of the present experiment, in a water depth of 8 m. The sand used for dyeing was obtained from Caroline Bay and had a median diameter of 2.77 ϕ.

The dyed tracer was slightly coarser with a median diameter of 2.72 ϕ. This grain size data was determined by rapid sediment analyser which, as was suggested in section 3.3.4.1, produces larger grain sizes than sieving. The median grain size for Caroline Bay sand determined by sieving during the present study was 3.21 ϕ and therefore the dyed sand used by Kirk probably had a sieving equivalent median diameter of 3.16 ϕ, which falls into the very fine sand size class. Over a period of 3.9 days Kirk obtained an average transport rate of 0.46 $m^3\ m^{-1}\ day^{-1}$ which compares well with the average value of 0.38 $m^3\ m^{-1}\ day^{-1}$ obtained during the first four days of the present study for very fine sand. In calculating his transport rate Kirk used a value of 0.10 m for the thickness of the mobile layer. This was estimated from burial patterns as indicated by the dispersion patterns in conjunction with estimates from other studies. In the present study the average value obtained for the thickness of the mobile layer during the first four sample runs was 0.089 m.

Heathershaw and Carr (1977) used radioactive tracers to estimate transport rates of fine sand in Swansea Bay, U.K., in an area subject to strong tidal currents of 1 - 2 $m\ s^{-1}$ and a persistent swell. At one site in an average water depth of 10 m radioactive glass particles having a mean grain size of 2.55 ϕ were released. Over a period of 342 days a typical transport rate of 0.21 $m^3\ m^{-1}\ day^{-1}$ was obtained. This rate varied between 0.17 $m^3\ m^{-1}\ day^{-1}$ and 0.62 $m^3\ m^{-1}\ day^{-1}$. These figures are significantly greater than those obtained during the present study for fine sand for the final three sample runs. This may be a result of the strong tidal currents and persistent swell occurring at the experiment site in Swansea Bay. The thickness of the mobile layer measured by Heathershaw and Carr was in the order of 0.15 m. This is twice the magnitude of the average value of 0.069 m obtained for fine sand for the final three sample runs in the present experiment.

Lees (1981) made sediment transport measurements in the Sizewell-Dunwich area, East Anglia, U.K., using fluorescent tracers. The fluorescent sand used had a mean grain size of 2.0 ϕ which lies on the boundary between the fine and medium sand size classes. The site of the experiment was in a water depth of 5 m in an area subject to tidal flows with maximum velocities reaching 1.5 m s^{-1}. Lees obtained transport rates of 0.052, 0.169, 0.050 and 0.064 m^3 m^{-1} day^{-1} averaged over 2, 3, 45 and 114.5 days respectively. The last two values are 5.0 - 6.4 times greater than the average obtained for fine sand and 1.8 - 2.3 times greater than the average obtained for medium sand for the final three sample runs in the present experiment. Again, the strong tidal currents may be the reason for the higher transport rates. The estimated thicknesses of the mobile layer used in the calculation of transport rates were 0.013, 0.023, 0.112 and 0.165 m respectively and the equilibrium thickness was thought to be 0.17 m. The equivalent values for the final three sample runs in the present experiment were 0.050, 0.085 and 0.071 m respectively for fine sand and 0.053, 0.074 and 0.069 m respectively for medium sand.

Courtois and Monaco (1969) used radioactive sand to determine transport rates on the Roussillon coast, France. The tracer sand used had an average grain size of 1.79 ϕ and was dumped 220 m out from shore in a water depth of 4 m. Initially the sediment moved south with a maximum measured rate of 0.645 $m^3\ m^{-1}\ day^{-1}$ and then it moved north reaching a maximum rate of 0.840 $m^3\ m^{-1}\ day^{-1}$. Later in the experiment rates of 0.036 and 0.051 $m^3\ m^{-1}\ day^{-1}$ were measured over 9 and 10 day periods respectively. The latter rates compare well with the average rate of 0.028 $m^3\ m^{-1}\ day^{-1}$ obtained for medium sand for the final three sample runs in the present experiment. The estimated thickness of the mobile layer throughout the experiment in France ranged from 0.14 - 0.19 m. In the present experiment the calculated thickness of the mobile layer ranged from 0.053 - 0.074 m for medium sand for the final three sample runs.

Although no quantitative results were obtained for the pebble size class the distributions of the recovered tracer pebbles shown in figure 4.9 and the distribution of tracer pebbles with depth shown in figure 4.17 can be compared with similar studies carried out overseas.

Steers and Smith (1956) working at Scott Head Island, Norfolk, U.K., dumped radioactive tracer pebbles a distance of 460 m seaward of the normal high water mark in a water depth averaging 5.6 m. The pebbles had an average major diameter of 51 mm and a specific gravity of 2.4 $g\ cm^{-3}$. The seafloor at this site consisted of firm sand with some shingle. Generally the tracer pebbles moved landward and after 40 days the maximum movement recorded was approximately 79 m.

Kidson, Carr and Smith (1958) deposited radioactive tracer pebbles 670 m offshore from Orfordness, Suffolk, U.K., in a water depth averaging 7 m. The size of the tracer pebbles used is not given but they were matched to the natural sediment in the area. Over a period of approximately 40 days the area around the dump site was surveyed eleven times and contact with the tracer pebbles was made on eight occasions. The experiment showed that no movement at all took place, not even radial spreading of the pebbles on the seafloor around the dump.

Kidson and Carr (1959) extended the earlier work at Orfordness by dumping radioactive tracer pebbles at four sites, 203, 213, 323 and 670 m, respectively, offshore. The two innermost sites were in a water depth of approximately 5 m. All four sites showed the same pattern of movement. The pebbles moved in all directions but had a slightly greater tendency to travel landward. The measured dispersal of 46 m or less over a 2 month period, which was characterised by weather and wave conditions ranging from calm to gale, was considered to be remarkably small.

Crickmore, Waters and Price (1973) released radioactive tracer pebbles at four sites with water depths of 9, 12, 15 and 18 m, respectively, offshore from Shoreham-by-Sea, West Sussex, U.K. The 15 m site was abandoned because an old mine was found that could not be relocated at a later date for destruction. The tracer pebbles used in the experiment ranged in size from 19 - 38 mm median diameter and the seafloor at the experimental sites consisted of "natural shingle". Over a period of 20 months the pebbles moved landward 40 m in the 9 m water depth and 15 m in the 12 m water depth while in the 18 m water depth no net pebble movement was recorded. After one winter analysis of the vertical distribution of the tracer pebbles in the 9 m and 12 m water depths showed that they were confined to the surface 0.050 m. After two winters the tracer pebbles were found to be mixed to depths of 0.125, 0.050 and 0.060 m in the 9, 12 and 18 m water depths respectively.

In general these studies show that the movement of pebbles on the seafloor is variable but when movement occurs it is generally in a landward direction, as was the case in the present study. With the exception of Steers and Smith (1956), who used pebbles with a lower specific gravity, the recorded movement of pebbles over the time periods studied was relatively small. This was also the case in the present study where the greatest recorded distance moved by a pebble was 30 m in 2.3 months. The distribution of tracer pebbles with depth in the present study showed that they were confined to the surface 0.050 m (fig. 4.17), the same depth that Crickmore, Waters and Price (1973) obtained for two sites in 9 and 12 m of water respectively. They found that the value at the shallower depth increased to 0.125 m after a longer time period and it seems likely that the depth of mixing in the present study would also increase with time.

4.7.4.6 Mixing Time

One assumption made during a tracer study is that sufficient time following injection is allowed to ensure that tracer behaviour is independent of the manner in which it was introduced (Greer and Madsen 1979). That is, if tracer material is simply dumped on the seabed surface sufficient time should be allowed for it to become fully incorporated into the mobile layer. Samples taken prior to this time will give excessive estimates of the actual transport rates. There are no reliable guidelines as to how much time is required for mixing to take place at a specific site. Heathershaw and Carr (1977) found that there was a point in their transport estimates where the mobility of the tracer decreased to a low and comparatively steady value. This occurred from 2 - 7 days after injection and this was taken as the estimated time for mixing to occur. In the present study all transport rates were found to decrease markedly after the first four sample runs. It is therefore assumed that it took from 5 - 10 days for mixing to occur and long-term sediment transport rates should be based on measurements made after this time, that is, on estimates made from the final three sample runs.

4.7.4.7 Regression Analysis

The aim of the regression analysis was to establish relationships between the average grain velocities or the sediment transport rates and wave or wave-dependent parameters so that these relationships could be used to predict long-term sediment transport rates based on the available wave data. Timme and Pollard (1965) note that such a procedure is difficult and is unlikely to succeed due to the complex nature of waves at any particular point, in their case along a beach, and because of the undefined relationship between this and other points.

Average grain velocities were used in the analysis in case no relationships were found between the sediment transport rate and the wave or wave-dependent parameters. If in such cases a long-term average grain velocity could be determined a long-term estimate of the sediment transport rate could be calculated from equation 4.4 by estimating the thickness of the mobile layer.

The main problem with the regression analysis was the lack of data points available, especially after splitting the data into two groups. Another problem was that only the magnitudes of the average grain velocities and sediment transport rates were used and no account was taken of the direction of movement.

The relationships found for very fine and fine sand, shown in tables 4.12 and 4.13, were for the first four sample runs only and in order to use these for long-term predictions further assumptions regarding how much any calculated sediment transport rates should be reduced are required. All other significant regressions were for the final three sample runs and can be used for long-term estimates, although for granules an estimated thickness of the mobile layer would also be required. Long-term predictions using these relationships are presented in chapter 8.

4.7.4.8 Sediment Sorting

It was noted in section 1.3 that the theories of wave-induced nearshore sediment transport indicate that the relationships between wave-induced oscillatory currents and nearshore sediment transport are complex but sensitive. According to some of the theories it would be possible to have a simultaneous movement of coarse sediment landward and fine sediment seaward. A simple relationship between grain size and sediment transport rate could not, therefore, be expected from this experiment. Examination of the results shows that the relationship between grain size and sediment transport rate was, in fact, highly variable, both between individual values and between the numerical average values. In many cases there was an increase in the transport rates as grain size increased. For example, coarse sand moved at a numerical average rate of 0.013 $m^3\ m^{-1}\ day^{-1}$ over the final three sample runs while very coarse sand moved at a numerical average rate of 0.019 $m^3\ m^{-1}\ day^{-1}$ over the same period.

In order to obtain a clearer picture of the differential transport or sorting of the various grain sizes diagrams were drawn showing the centroid displacement for the size classes measured as departures from the preceeding sample run. Only the final three sample runs were considered to ensure that there had been sufficient time for both mixing and sorting to occur. The diagrams are shown in figure 4.19. For sample run 5 very fine sand, fine sand and medium sand moved a net distance seaward while coarse sand, very coarse sand and granules moved a net distance landward. For sample run 6 there was a net seaward movement for all size classes and for sample run 7 there was a net

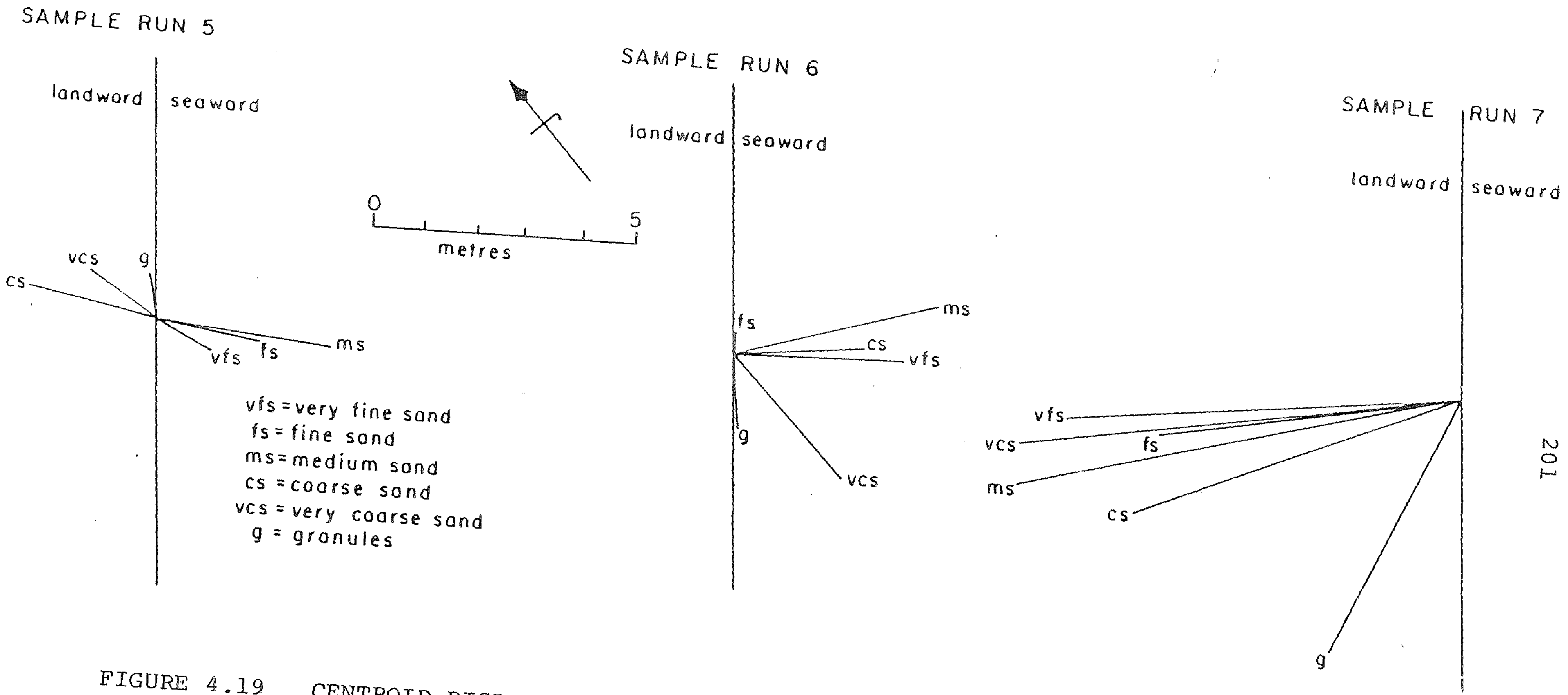


FIGURE 4.19 CENTROID DISPLACEMENT FOR SAMPLE RUNS 5, 6 AND 7 MEASURED AS DEPARTURES FROM THE PREVIOUS SAMPLE RUN, EXPERIMENT 1.

landward movement for all size classes. The pattern of movement for sample run 5 supports the theories of both Cornish (1898) and Cornaglia in Zenkovich (1967, p. 101) that suggest the possibility of simultaneous movement of coarse and fine sediments in opposite directions. The pattern for sample run 7 could support all of the theories outlined in section 1.3 while the pattern for sample run 6 does not clearly support any of the theories.

The index of net movement (table 4.18), calculated from the tracer dispersion patterns, showed that there was a net landward movement of all size classes but that there was an increasing tendency for landward movement with increasing grain size (fig. 4.18). This can be related to the asymmetric nature of wave-induced oscillatory currents in the nearshore. Cornish (1898) stated that the high velocity under the crest could be sufficient to move coarse particles landward but that the low velocity under the trough could be insufficient to move the particles in a seaward direction. This theory could be extended by stating that with increasing grain size there would be an increasing tendency for landward movement because the threshold for movement would be exceeded more frequently and for longer time periods under the crest than under the trough. This would lead to a pattern of movement such as that found using the index of net movement.

4.7.4.9 Rollability Analysis

The rollability analysis was designed to identify factors other than grain size (which was standardised) and specific gravity (which was assumed to be constant) which affect sediment transport. No trends were found with respect to average grain weight. This is not surprising because grain weight is directly related to grain size. The rollability tests showed no trends in the median rolling times of the various samples. This may indicate that grain shape is not an important factor influencing transport for the range of particle sizes tested. A much more likely explanation, however, is that because the sediment collected for dyeing was from a beach environment it had already been well pre-sorted by waves and therefore did not contain a full spectrum of particle shapes. This would probably preclude differences in particle shape being found in subsequent analysis of this type.

4.7.4.10 Tracer Accounting

The techniques used to calculate the amounts of tracer that could be accounted for during this experiment could be expected at best to give rough estimates only. Alternative techniques that could have been used would have employed the dispersion patterns and depth of mixing of the tracer. These techniques, however, would also be subject to various assumptions and errors would be introduced. The two major difficulties with any of the techniques were, firstly, to establish the total number of luminophors in each size class in a sample and, secondly, to establish how many grains per gram there were in each size class. Both of these factors would have a great affect on the results no matter what technique was used.

The figures given in table 4.20 do show a decrease in the amount of tracer accounted for after sample run 4 for sizes up to medium sand while the maximum values accounted for in the coarser size classes were not reached until later. This may indicate that some of the finer tracer material left the sampling area after sample run 4. The fact that on several occasions more than 100% of the tracer was accounted for is simply a reflection on the inaccuracies of the accounting technique used.

4.8 IRONSAND TRACER

This section describes the analysis of and results from the ironsand tracer.

4.8.1 Grain Size, Magnetic Properties And Specific Gravity

A sample of sand from Carters Beach was sieved to determine the percentage that fell into each of the size classes defined earlier for the fluorescent tracer. The results showed that 52.3% fell into the very fine sand class and 47.6% fell into the fine sand class. This meant that of the 90 kg released on the seafloor 47 kg was very fine sand and 43 kg was fine sand.

Detection of the ironsand was to be by its magnetic susceptibility which could be determined by using a Frantz isodynamic magnetic separator. The separator consists of an inclined vibrating chute surrounded on either side by the pole-pieces of an electromagnet. The tilt of the chute is adjustable both longitudinally and transversely. A sample is fed into the top of the chute in a regulated flow from a hopper. As the grains travel down the chute the magnetic field pulls the more magnetic grains up slope to one side. At its lower end the chute is separated by a longitudinal divider which feeds the grains into two collecting buckets. The amperage on the electromagnet can be set at various levels to select grains of differing susceptibilities. By weighing the grains collected in each bucket after a sample has been separated it is possible to determine the percentage of the sample that is susceptible at that setting of the tilt and amperage on the separator.

In order to determine the amount of Carters Beach sand that would be detectable several samples were run through the Frantz isodynamic magnetic separator at the Department of Geology, University of Canterbury, at various amperage settings. Samples from the sediment survey were also analysed at the same settings to determine the background levels of magnetic material. Both the longitudinal and transverse tilt were set at 20°. The results are shown in table 4.21. As the current increased the amount of detectable material increased. However, at the same time the background levels also increased and so a trade off had to be made between the two. After studying the figures in table 4.21 it was decided that the 0.5 A setting was best for very fine sand and the 1.0 A setting was best for fine sand.

TABLE 4.21 DETECTABLE QUANTITIES OF CARTERS BEACH SAND AND BACKGROUND LEVELS FOR VARIOUS AMPERAGES ON THE FRANTZ ISODYNAMIC SEPARATOR.

CURRENT SETTING (A)	VERY FINE SAND		FINE SAND		BACKGROUND LEVEL %	
	%	kg	%	kg	VERY FINE SAND	FINE SAND
0.5	78	37	12	5	2	2
1.0	93	44	47	20	13	14
1.5	96	45	61	26	-	-

Samples of the magnetic fractions of very fine sand and fine sand were taken for more detailed size analysis and specific gravity determinations. The samples were sieved and the mean grain size calculated. For very fine sand the mean grain size was 0.0994 mm and for fine sand it was 0.1466 mm. Samples were then analysed for specific gravity with a pycnometer using the technique of Krumbein and Pettijohn (1938). The average specific gravity was found to be 4.04 g cm^{-3} for very fine sand and 3.48 g cm^{-3} for fine sand.

4.8.2 Settling Equivalence

"Settling velocity" is defined as the constant terminal speed at which a particle falls through a fluid which is essentially at rest (Baumgaertner 1978). It is a function of the viscosity and specific gravity of the fluid and of the size, shape, and specific gravity of the particle (Baumgaertner 1978). It is possible that grains of different sizes and different specific gravities have equivalent settling velocities.

For the present study two techniques were used to determine the grain sizes of light minerals whose settling velocities were equivalent to the heavy mineral settling velocity of the magnetic fractions of the Carters Beach sand.

4.8.2.1 Stokes' Law

Stokes' law can be used to calculate the settling velocity of a particle in a fluid (Schreiber 1978). Stokes' law is:

$$\omega = g\ (\rho_s - \rho)\ D_s^{2} / 18\ \mu \qquad 4.13$$

where ω = settling velocity (cm s^{-1})

g = gravitational acceleration (cm s^{-2})

ρ_s = grain specific gravity (g cm^{-3})

ρ = fluid specific gravity (g cm^{-3})

D_s = grain diameter (mm)

μ = fluid molecular viscosity (poise)

If light and heavy mineral grains have equivalent settling velocities then:

$$\omega_l = \omega_h$$

$$\Rightarrow \quad g(\rho_l - \rho)\ D_l^{2} / 18\ \mu = g(\rho_h - \rho)\ D_h^{2} / 18\ \mu$$

$$\Rightarrow \quad (\rho_l - \rho)\ D_l^{2} = (\rho_h - \rho)\ D_h^{2}$$

$$\Rightarrow \quad D_l = \sqrt{(\rho_h - \rho)\ D_h^{2} / (\rho_l - \rho)} \qquad 4.14$$

where ω_l and ω_h = settling velocities of light and heavy minerals respectively (cm s^{-1})

ρ_l and ρ_h = grain specific gravity of the light and heavy minerals respectively (g cm^{-3})

ρ = fluid specific gravity (g cm^{-3})

D_l and D_h = grain diameter of the light and heavy minerals respectively (mm)

By substituting in the values of specific gravity and grain size determined for the magnetic fractions of Carters Beach sand and by assuming ρ = 1.03 g cm^{-3} and ρ_l = 2.65 g cm^{-3}, values of D_l = 0.1354 mm and D_l = 0.1803 mm were obtained for very fine sand and fine sand respectively.

4.8.2.2 Rapid Sediment Analyser

The "Pelagic Electronics Model 8010 Rapid Sediment Analyser" in the Physical Laboratory, Department of Geography, University of Canterbury was also used to determine settling equivalent sizes for the light and heavy minerals. The rapid sediment analyser consists of two 1 m long columns of water separated at the bottom by a differential pressure transducer. Particles are placed on a tray and released into the main column of water. This increases the effective density of this column and causes a pressure differential with respect to the reference column. The pressure differential is recorded by a T - Y recorder. From the output it is possible to measure the median settling time for a sample. The settling time is equivalent to the settling velocity because all samples fall through the same distance.

Samples of fluorescent dyed, tracer grains were sieved to ¼ ϕ intervals. Two 0.5 g samples from each sieve fraction were weighed out and wetted with a drop of detergent to release the surface tension and prevent floating. Two samples from the magnetic fractions of the very fine sand and fine sand from Carters Beach were also weighed out. These samples were not sieved to ¼ ϕ intervals. All of the samples were then run through the rapid sediment analyser and the median settling time was measured. From the fluorescent grains a graph of average median settling time versus grain diameter was plotted and is shown in figure 4.20. The average median settling times for the two heavy mineral samples were entered on figure 4.20 and the equivalent grain sizes read off.

4.8.2.3 Summary

Table 4.22 summarises the settling equivalence data. For both the very fine sand and the fine sand the settling equivalent size determined by the rapid sediment analyser is smaller than that determined by Stokes' law. This could be due to particle shape, errors in the rapid sediment analysis or in specific gravity determinations. In addition, for Stokes' law a mean grain size was used whereas for the rapid sediment analysis a median settling time was used.

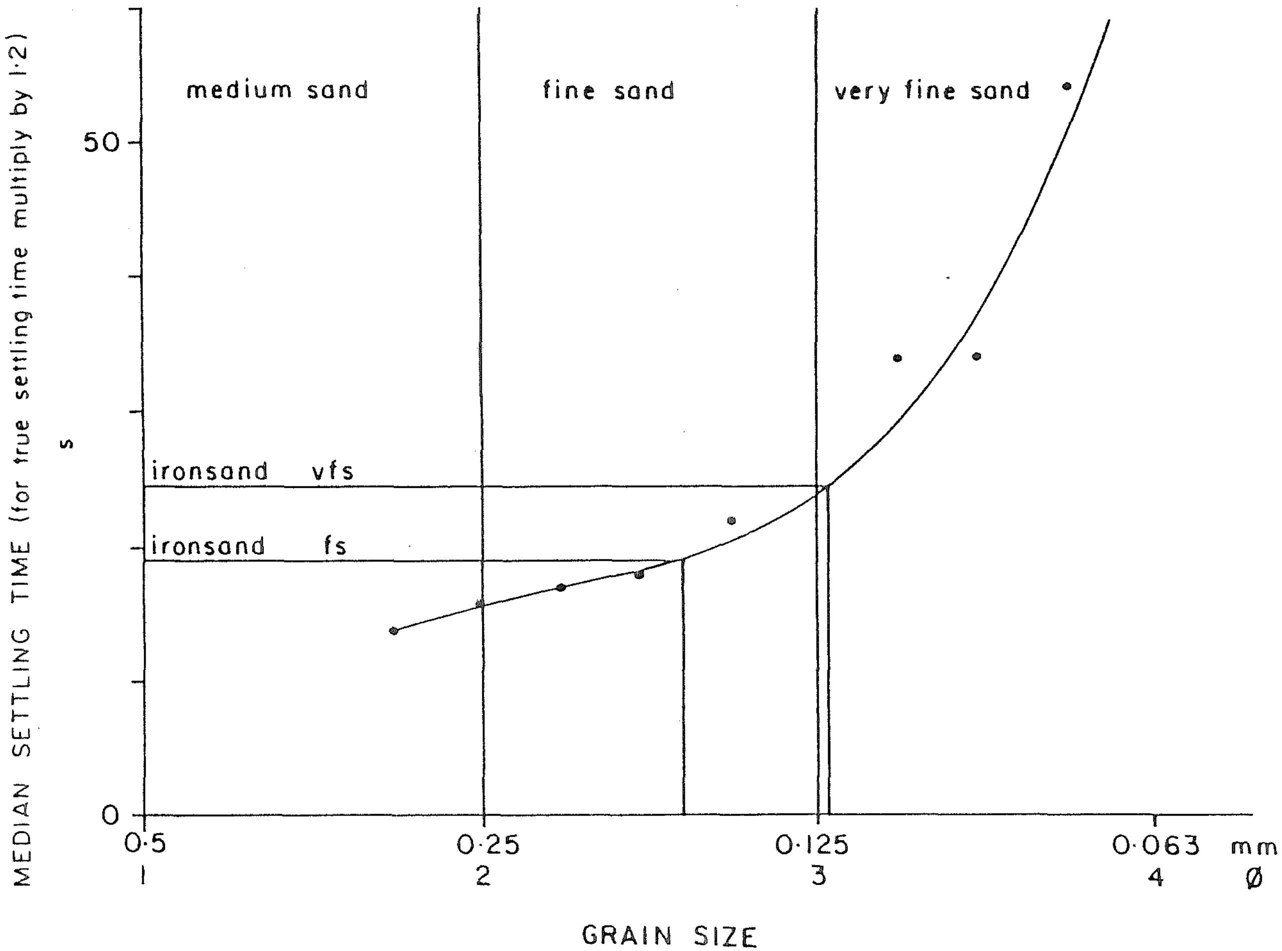


FIGURE 4.20 AVERAGE MEDIAN SETTLING TIME FROM THE RAPID SEDIMENT ANALYSER VERSUS GRAIN SIZE FOR THE FLUORESCENT TRACER.

TABLE 4.22 SUMMARY OF SETTLING EQUIVALENCE DATA FOR CARTERS BEACH SAND.

	VERY FINE SAND (mm)	FINE SAND (mm)
Mean grain size (sieve)	0.0994	0.1466
Settling equivalent size (Stokes)	0.1354	0.1803
Settling equivalent size (RSA)	0.1220	0.1645

The figures in table 4.22 show that for very fine sand the settling equivalent size from Stokes' law falls into the fine sand size class and the size determined from the rapid sediment analyser falls very close to the upper boundary of the very fine sand size class. Therefore it was possible that the magnetic fraction of very fine sand would behave similarly to the fine sand fraction of the fluorescent tracer. For fine sand the magnetic fraction should have behaved the same as the fine sand fluorescent tracer.

4.8.3 Analysis

After samples had been analysed for fluorescent tracer the fine sand and very fine sand fractions were taken for analysis in the Frantz isodynamic separator. Very fine sand samples were repeatedly split using a micro-sample splitter to reduce the sample size before being run through the separator. The percentage of a sample that was magnetic at 0.5 A for very fine sand and 1.0 A for fine sand was measured and recorded. The appropriate background level was subtracted and the resulting values were then used to plot dispersion patterns.

4.8.4 Results

4.8.4.1 Very Fine Sand

No ironsand tracer could be detected above the background level. Approximately 90% of the sand on the seafloor is very fine sand and the dilution of the ironsand tracer was obviously too great. A check on the maximum concentration of fluorescent particles found in the experiment showed that it was equivalent to 0.22% of the sample, a figure much lower than could be detected for the ironsand with any certainty.

4.8.4.2 Fine Sand

Only sample run 4 had enough samples with ironsand levels above the background level to warrant the drawing of a dispersion pattern. The pattern is shown in figure 4.21(a). Before this pattern could be compared with the results from the fluorescent tracer the fluorescent concentrations had to be reduced so that the sensitivity level was similar to that of the magnetic tracer. To do this the fluorescent concentrations were converted to percentages and divided by 4.5 because there was 4.5 times more fluorescent fine sand released. The dispersion pattern produced is shown in figure 4.21(b).

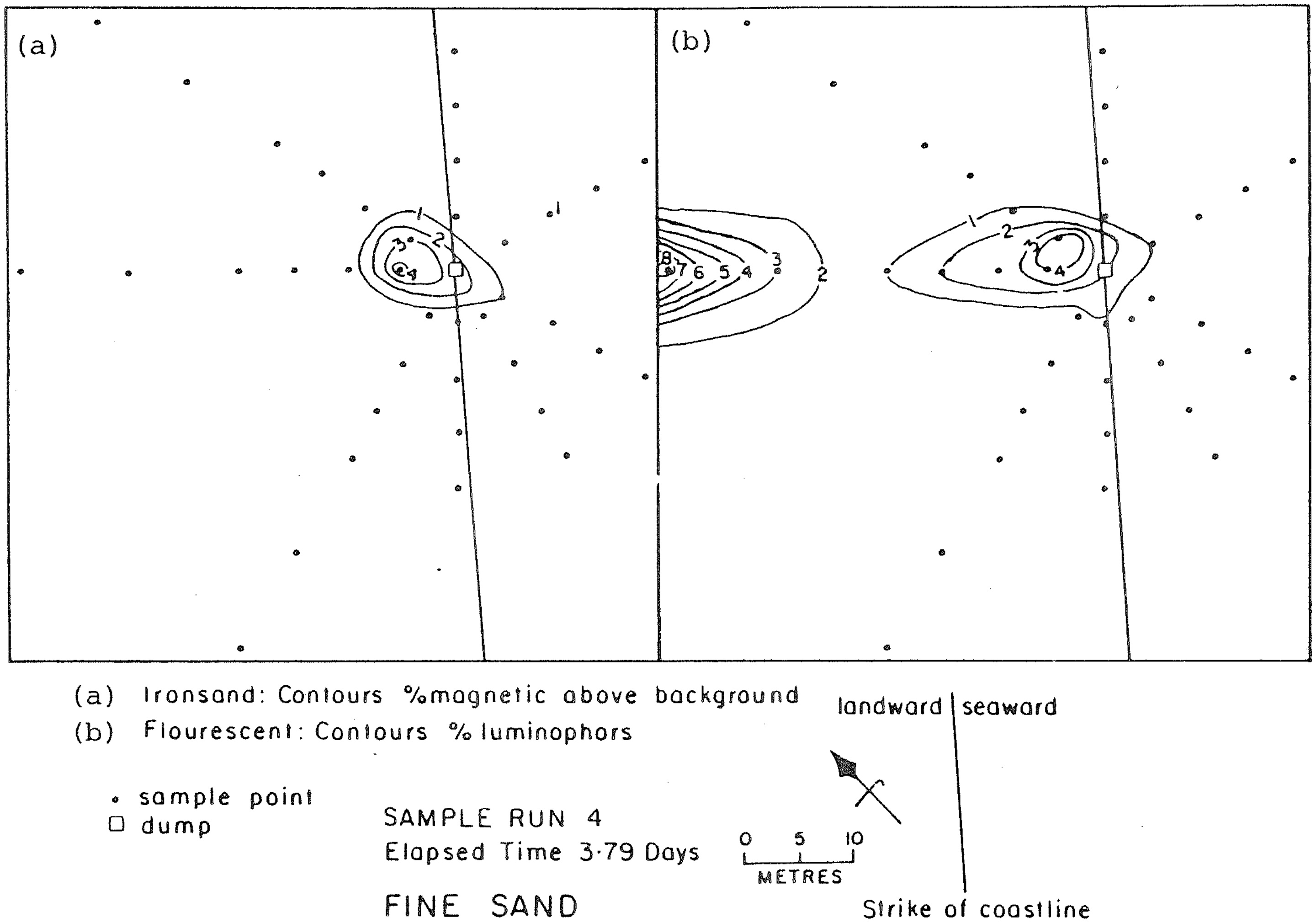


FIGURE 4.21

(a) IRONSAND DISPERSION PATTERN FOR SAMPLE RUN 4.

(b) DISPERSION PATTERN FOR FLUORESCENT FINE SAND WITH CONCENTRATIONS CONVERTED TO EQUIVALENT PERCENTAGES.

4.8.5 Discussion

The two dispersion patterns shown in figure 4.21 show that there were considerable differences in behaviour between the fluorescent tracer and the ironsand for the fine sand size class. However, because only four samples contained ironsand tracer in levels above the background it is not possible to place much confidence in these results. Because of this and the fact that no ironsand tracer was found in the very fine sand size class it is not possible to draw conclusions with respect to settling and hydraulic equivalence.

With respect to sediment tracing the ironsand did not make a good tracer because of its poor sensitivity. Sensitivity could be increased by:

a) Using a very concentrated ironsand with a high magnetic susceptibility.

b) Using a very large quantity of ironsand.

c) Working in an area where background levels are very low.

It should be remembered that heavy minerals do not behave the same as light minerals and that this limits the use of ironsand as a tracer to special situations. These might include studies to see how light and heavy minerals become separated on a beach or experiments such as the present one which was concerned with looking at settling and hydraulic equivalences. Because of the poor sensitivity of ironsand as a tracer such studies might best be carried out by dyeing the ironsand prior to release with a fluorescent pigment. Provided different coloured dyes were used it would be possible to distinguish between light and heavy minerals and each would have equivalent sensitivity. It would be necessary, however, to concentrate the ironsand prior to release to ensure that only heavy minerals were dyed.

4.9 SUMMARY OF RESULTS

Results from the fluorescent tracer have shown that at the site of the experiment, 1.4 km offshore in a water depth averaging 7.6 m, there is a net landward movement of sediment ranging in size from 0.063 - 19.050 mm median diameter. There are, however, periods when net seaward movement may occur.

Sediment transport rates decreased after the first four sample runs suggesting that it took from 5 - 10 days for complete mixing of the tracer into the mobile layer. Therefore results from the final three sample runs provide the best estimates of long-term sediment transport rates. The numerical mean sediment transport rate for the final three sample runs ranged from 0.008 m^3 m^{-1} day^{-1} for granules to 0.028 m^3 m^{-1} day^{-1} for medium sand.

Some statistically significant linear relationships were found between both the average grain velocities and the sediment transport rates and wave or wave-dependent parameters. These relationships were all positive and indicate that an increase in the wave or wave-dependent parameters will cause a proportionate increase in the average grain velocity and the sediment transport rate. The finding of these relationships and the pattern of movement of the fluorescent tracer suggest that wave-induced horizontal oscillatory currents are the dominant transporting agent, as was proposed in chapter 3.

The relationship between grain size and sediment transport rate was, as expected, highly variable. When diagrams were drawn for the final three sample runs showing centroid displacement as departures from the preceding sample run it was seen that the sorting pattern was variable. The pattern for sample run 5 indicated a landward transport of coarse sediments and a seaward transport of fine sediments. This pattern supports the theories of both Cornish (1898) and Cornaglia _in_ Zenkovich (1967, p. 101) which allow for simultaneous transport of different sized sediments in opposite directions. The pattern for sample run 7 indicated landward movement for all sizes which could support all of the theories outlined in section 1.3. The pattern for sample run 6 indicated a seaward movement for all size classes and does not clearly support any of the theories.

The index of net movement showed that there was a net landward movement for all grain sizes but that there was an increasing tendency for landward movement with increasing grain size. This finding could be explained by extending the theory of Cornish (1898) by stating that with increasing grain size there would be an increasing tendency for landward movement because the threshold for movement would be exceeded more frequently and for longer time periods under the crest than under the trough.

The use of the magnetic properties of ironsand for sediment tracing purposes was not successful because of the poor detection sensitivity. For this reason it was not possible to compare the transport of sediments of differing specific gravities or to test the prediction of the relative transport rates from settling equivalence as had initially been planned.

CHAPTER V

FLUORESCENT TRACING OF VERY FINE SAND

5.1 INTRODUCTION AND AIMS

Chapter 3 described aspects of the nearshore environment at Timaru that were considered important with respect to nearshore sediment transport. These data were then used to calculate a seaward limit to the very active littoral zone and to determine the percentage of time calculated threshold velocities were exceeded. All of the information combined indicated that there was considerable potential for nearshore sediment transport in the study area and that wave-induced horizontal oscillatory currents were the dominant transporting agents. Experiment 1, described in Chapter 4, confirmed that a wide size range of sediment could be transported on the seafloor 1.4 km offshore to the north of Timaru Harbour and that wave-induced horizontal oscillatory currents appeared to be the dominant transporting agent. Attempts were made to find relationships between average grain velocities or sediment transport rates and wave or wave-dependent parameters. Although some statistically significant relationships were found more data were required.

For this reason a second seafloor tracing experiment was planned and executed. The experiment used fluorescent dyed tracer but differed from experiment 1 in a number of ways. Firstly, only very fine sand, the size which dominates the seafloor in the study area (fig. 3.4(a)), was used. Secondly, the experiment was located to the south of Timaru Harbour entrance channel in a greater water depth than experiment 1; and thirdly, the sample tubes were modified to provide improved core information.

The following aims were formulated for the experiment:

a) To determine both the rate and direction of transport of very fine sand on the seafloor to the south of Timaru Harbour entrance channel.

b) To look for relationships between the measured transport rates and wave and wave-dependent parameters.

c) To compare the measured rates of movement with those obtained for very fine sand during experiment 1.

d) To combine the results with those from experiment 1 and look for possible relationships with wave-dependent parameters.

This chapter outlines the methodology and findings of this experiment, which will be referred to as experiment 2.

5.2 LOCATION OF THE EXPERIMENT

Two factors were considered when choosing the exact location for experiment 2. Firstly, because available boat time was limited accessibility was important. It was desirable that the site be within 30 minutes boat time from the port which is equivalent to a distance of about 3 km. Secondly, and more importantly, shipping routes had to be considered, particularly those usually taken by fishing boats when entering and leaving the port. After consultation with the Harbourmaster at Timaru two options existed - either the experiment could be sited immediately offshore from South Beach or it could be placed some distance offshore. The second option was chosen because deeper water was preferred and because working close to the beach can be difficult due to the intensity of the wave action there.

The location of the site chosen is shown in figure 3.8, lying just to the south of a large buoy marking the entrance channel to the port. It was hoped that ships and fishing boats would tend to avoid the buoy, and hence the experiment site, but, as will be shown later, this was not the case. The water depth at the experiment site averaged 12.2 m.

5.3 PREPARATION OF FLUORESCENT TRACER

Because obtaining large quantities of sand from the seafloor is difficult the sand to be dyed for this experiment was obtained from the foreshore of the beach in Caroline Bay. The sand was taken to the Physical Laboratory, Department of Geography, University of Canterbury, where it was washed and air dried. The sand was then dyed with a fluorescent pigment using the dyeing machine (fig. 4.1) described in section 4.3.2. A total of 337 kg of fluorescent tracer sand was produced.

The sand from the foreshore in Caroline Bay, and hence the tracer sand, differed in grain size from the sand on the seafloor at the experiment site. Figure 5.1 shows the grain size curves that resulted from sieving samples of tracer and seafloor sand. Table 5.1 lists grain size parameters for these samples and for a sample of Caroline Bay sand that was also sieved. The grain size parameters are defined in appendix 1. The tracer sand, with a mean grain size of 3.14 ϕ, was clearly coarser than the seafloor sand which had a mean grain size of 3.52 ϕ. The tracer sand was not as well sorted as the seafloor sand and was coarse-skewed while the seafloor sand was fine-skewed. In terms of the experiment these differences are taken to mean that the results are representative of a particular size fraction of the seafloor sediment. The grain size curve for the tracer sand in figure 5.1 shows that 90% of the tracer lay within the size range 2.30 - 3.65 ϕ. The amount of seafloor sand within this size range was 75.5%. The tracer sand therefore only represented the 75.5% of the seafloor sand which lay between 2.30 ϕ and 3.65 ϕ.

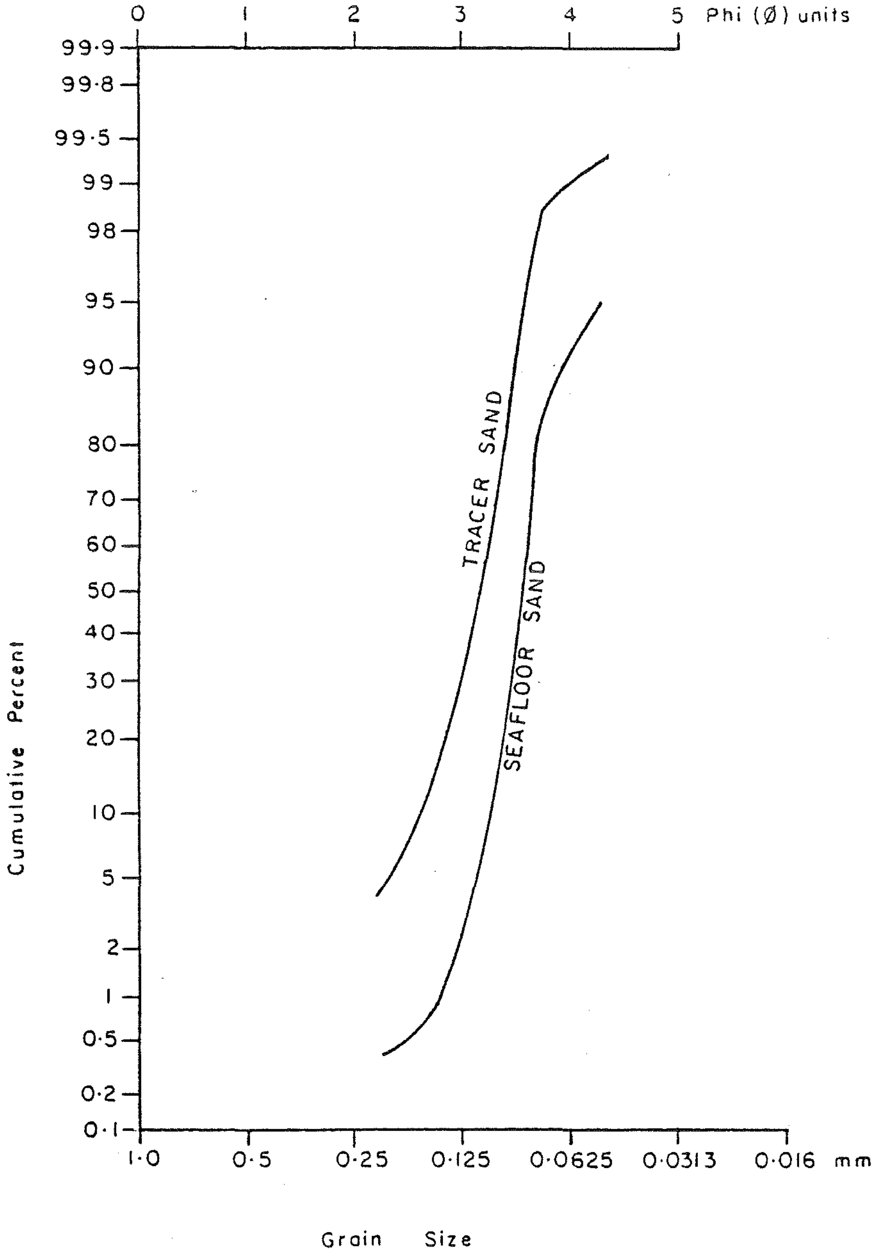


FIGURE 5.1 GRAIN SIZE CURVES FOR SAMPLES OF TRACER AND SEAFLOOR SAND, EXPERIMENT 2.

TABLE 5.1 GRAIN SIZE CHARACTERISTICS FROM FOLK (1974) (SEE APPENDIX 1) FOR SAMPLES OF CAROLINE BAY SAND, TRACER SAND AND SEAFLOOR SAND FROM THE SITE OF EXPERIMENT 2.

SAMPLE	MEAN GRAIN SIZE			SORTING		SKEWNESS	
	ϕ	mm	Class	Value	Verbal	Value	Verbal
Caroline Bay	3.18	0.1103	very fine sand	0.21	very well sorted	-0.15	coarse skewed
Tracer	3.14	0.1134	very fine sand	0.37	well sorted	-0.29	coarse skewed
Seafloor	3.52	0.0872	very fine sand	0.29	very well sorted	0.26	fine skewed

Using coarser tracer sand for this experiment was advantageous because it meant that a greater proportion of the tracer would be transported as bedload, the mode of transport under study. Lees (1981) used tracer sediment with a mean grain size 0.18 ϕ coarser than the native sand for a seafloor fluorescent tracer experiment in the Sizewell-Dunwich Banks area, East Anglia, U.K. Lees used the coarser tracer to restrict transport to bedload movement as much as possible.

Table 5.1 shows the changes in the grain size characteristics introduced by the dyeing process. Mean grain size was increased by 0.04 ϕ, the degree of sorting decreased and the degree of coarse-skewness increased. The small increase in mean grain size indicates that the dyeing process did not alter the grain size by a significant amount and the change in the sorting and skewness values probably resulted from a few aggregates that were formed during dyeing.

5.4 SAMPLING GRID AND TRACER RELEASE

As in experiment 1 both the rates and directions of movement of tracer were to be determined by the spatial integration technique. It was therefore decided that the sampling grid that had been recovered from the seafloor following the completion of experiment 1 would be re-used. All of the buoys, buoy-lines and shackles were replaced and one of the radial lines that had broken was also replaced. One modification made to the grid was to tie a number of knots in the inner end of each line corresponding to the number of that line. Each line could then be easily identified at the centre of the grid if the buoy marking the end of the line disappeared.

The grid was taken to the experiment site and laid in the same way as described in section 4.4. Again considerable difficulty was experienced in positioning the lines on the correct headings and the final orientation was determined by underwater compass. The lines were numbered anti-clockwise for this experiment. The final orientation of the grid and the location of the sample points are shown in figure 5.2.

The tracer was released using the same procedures as for experiment 1 (section 4.5). During the release there

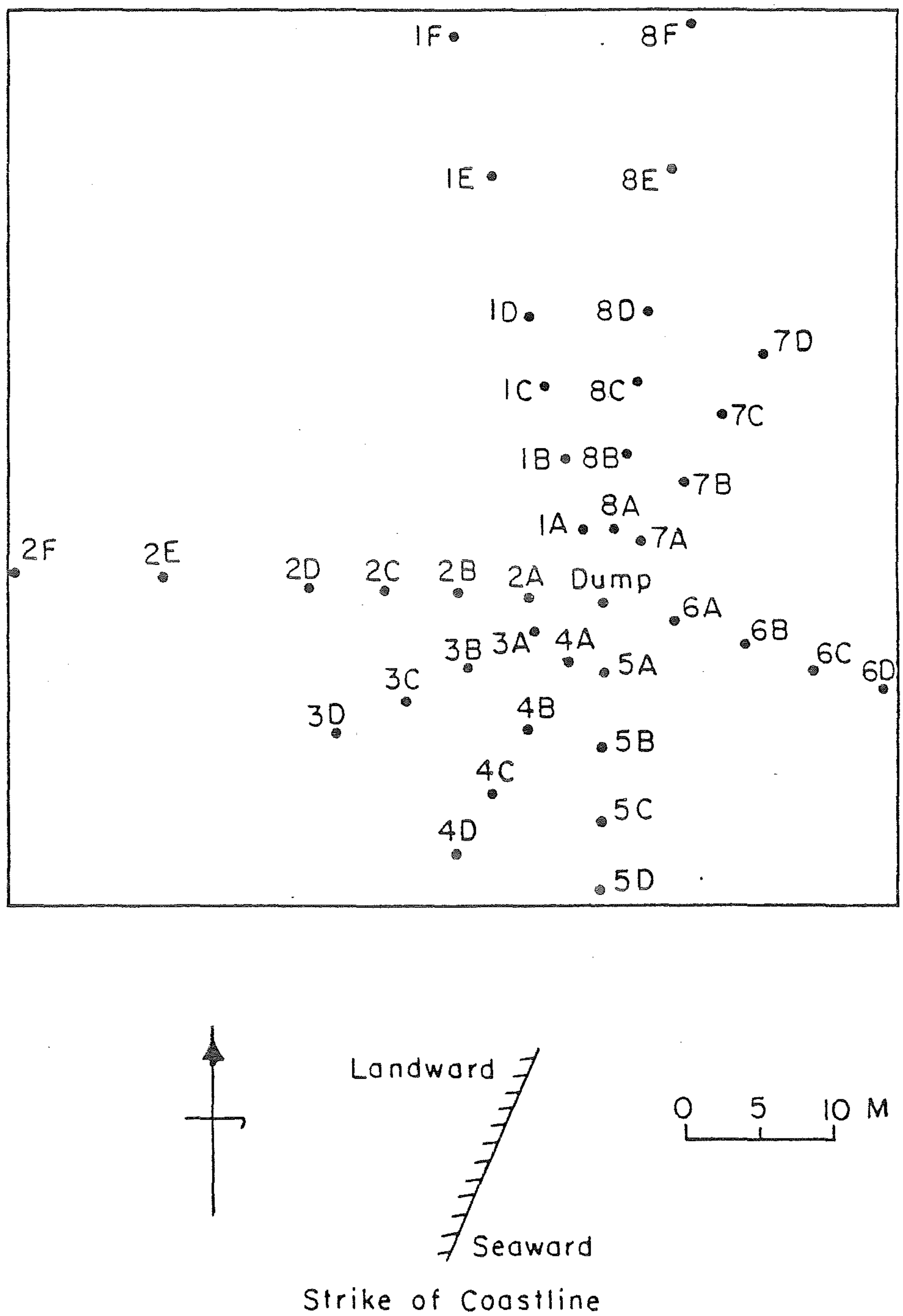


FIGURE 5.2 SAMPLING GRID FOR EXPERIMENT 2.

was zero visibility on the bottom but it was estimated that the tracer sand formed a mound approximately 1.5 m in diameter and 0.2 m high. Waves at the time of release were from the easterly quarter with $H_s = 0.76$ m and $T_s = 9$ s.

5.5 SAMPLE COLLECTION

Volumetric samples were collected from the sampling grid on five occasions following the release of the tracer sand. The first samples were collected after 1 day and the final samples after 21 days. Sample collection ended prematurely at this point when a fishing boat ran over and fouled the buoy-lines marking the grid. The boat had to return to Timaru Harbour to have rope removed from its propeller. Some time after this incident part of the grid was found floating in the harbour. Although the incident occurred at night and the buoys on the grid did not have lights, all local fishing companies and the Timaru Commercial Fishermans' Association had been notified before the experiment commenced. They had also been sent a copy of a map marking the location of the grid.

Both the sample tubes and the sampling procedure were slightly modified from those outlined in section 4.6 for experiment 1. Pistons were added to the sample tubes to exclude water from the sample and to provide suction to retain the sediment while the tube was extracted. The pistons consisted of two 3 mm thick rubber discs nailed to either side of a 10 mm thick plywood disc. Figure 5.3 shows one of these pistons diagramatically. The pistons were placed at the bottom of the core tubes prior to sampling. When a tube was driven in the piston remained on the sediment surface, as illustrated in figure 5.4. After extraction the tubes were tipped over and the lower end capped. The caps, which were tapered, had been turned out so that they fitted flush with the end of the tube.

Using these samplers each grid sample remained intact and this eliminated the necessity of taking separate cores to obtain data on the thickness of the mobile layer.

During the third sample run it was discovered that when the tubes were capped water was being forced into the core. This problem was largely eliminated for the final two sample runs by drilling a series of holes around the side of each cap to allow the water to escape.

Although the sample tubes had been improved considerably with the addition of the piston not all grid samples remained completely intact. The most frequent causes of disturbed samples were the presence of either crabs or large amounts of organic matter. Another problem that sometimes arose during the sampling was sediment sticking to the outside of the sample tube. This prevented the lid being placed on properly. Regularly wiping the sample tubes to remove this sediment was undesirable because some of the sample from the lower end of the tube could have been lost during the process.

Chapman and Smith (1977) also used sample tubes with pistons to obtain short cores during a fluorescent tracing experiment. They used a tightly fitting leather piston on

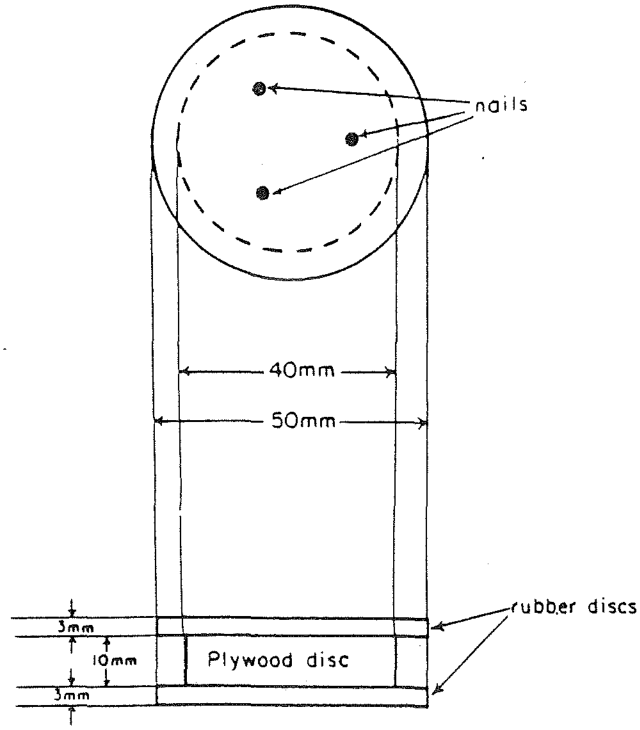


FIGURE 5.3 PISTON USED IN SAMPLING TUBES FOR EXPERIMENTS 2 AND 4.

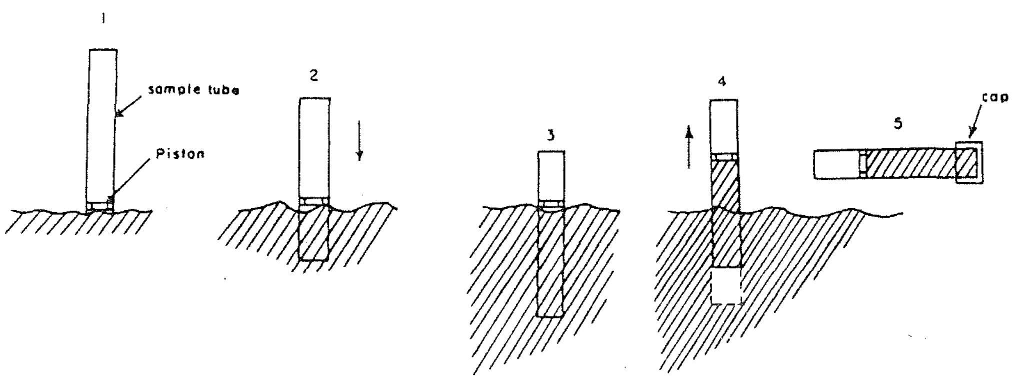


FIGURE 5.4 OPERATION OF SAMPLING TUBE WITH PISTON.

a dowelling handle which was withdrawn as the sample tube was driven into the sand. This created a slight negative pressure which helped to retain the sediment during extraction.

Sample collection involved two teams working from two small boats, each sampling alternative lines of the grid. The author and two other divers collected the samples. The author worked by himself from one boat using a "cartridge belt" system to carry the sampling tubes to the bottom. The "cartridge belt" enabled the correct sampling tube to be found easily even when water visibility was poor. This task had previously been one of the most time consuming elements in the whole sampling operation. The other two divers worked together, one selecting the correct tubes and the other taking the samples.

In addition to the grid samples a further sample was collected by the author at the dump site during each sample run. This and all other samples were easily collected in a 1 hour period.

For the first three sample runs all samples were returned to shore where they were plunged out of the tubes and cut into 5 cm sections, working from the top of the core. Each section was placed in a labelled plastic bag and an additional label was attached. The 5 cm sections were prepared because it had been hoped to determine sediment transport rates and directions for discrete depth intervals. This idea was abandoned later for two reasons. Firstly, in some samples the lower sections were contaminated by tracer from the top section; and secondly, the thickness of the mobile layer proved to be relatively small. All of the bagged samples were taken to the Physical Laboratory, Department of Geography, University of Canterbury, for analysis.

For the final two sample runs the sample tubes were returned to shore and taken to the laboratory before extraction. At the laboratory the samples were extracted and then all but the first few samples from sample run 4 were cut longitudinally and inspected under a UV light. A note was made of the depth of tracer mixing in the centre of the core, away from any contamination and smearing along the outside. The cores were again cut into 5 cm sections before being bagged for later analysis, although for sample run 5 any section of a core not containing tracer was discarded.

5.6 ANALYSIS

Only the top 5 cm section was analysed for the first three sample runs because it was clear from the inspection of samples from sample runs 4 and 5 that the initial depth of mixing would have been less than 5 cm.

Samples to be analysed were:

1. Spread out on newspaper and air dried.

2. Crushed between newspaper using a "rolling pin" to remove large aggregates that would have clogged the micro-sample splitter.

3. Weighed to give the total sample weight.

4. Repeatedly split using a micro-sample splitter until an amount suitable for counting remained (that is,

approximately 3 g or less).

5. The subsample was re-crushed using a rubber tipped pestle to ensure all aggregates were removed.

6. The subsample was weighed to 0.0001 g.

7. The subsample was placed on a clean sheet of paper and taken into a darkroom.

8. The subsample was spread so it was one grain layer thick and the luminophors present were counted using a UV light fitted with a magnifying glass. If the number was greatly in excess of 300 then the subsample was split again, weighed and recounted. A concentration of 1 luminophor in 2 g was the minimum concentration considered.

The total number of luminophors present in a particular sample, N_s, was then calculated from:

$$N_s = \sum_{i=1}^{s} n_i \, B_i \, / \, b_i \qquad 5.1$$

where N_s = total number of luminophors in the sample

s = the number of 5 cm core sections containing tracer (for sample runs 1 - 3, $s = 1$)

n_i = number of luminophors in the subsample from core section i

B_i = total weight of core section i (g)

b_i = weight of subsample from core section i (g)

The calculated values of N_s were converted to logarithms and used to draw dispersion patterns for each sample run. The x and y co-ordinates of the centroid of each pattern were then calculated from equations 4.1 and 4.2, with the tracer concentration at each sample point being replaced by the total number of luminophors present.

An average grain velocity V (magnitude and direction) for each sample run was calculated from the positional shifts of the centroid between successive sample runs.

The recorded depths of tracer mixing for sample runs 4 and 5 were averaged to provide estimates of the thickness of the mobile layer E. The calculated value for sample run 4 was used in sediment transport calculations for the first three sample runs.

Sediment transport rates, q, were calculated for each sample run using equation 4.4.

Data recorded by the wave recorder were used to calculate the wave and wave-dependent parameters defined in table 4.3. Regression analysis was then used to look for relationships between these parameters and the calculated average grain velocities and sediment transport rates from the tracer study. The regression analysis was run using the "Statistical Package For The Social Sciences" program on the University of Canterbury's "Prime 750" computer.

5.7 RESULTS

The dispersion patterns for each sample run are shown in figure 5.5. The calculated tracer centroid has been included on each pattern along with a line running through the dump point parallel to the coast and to the bottom contours.

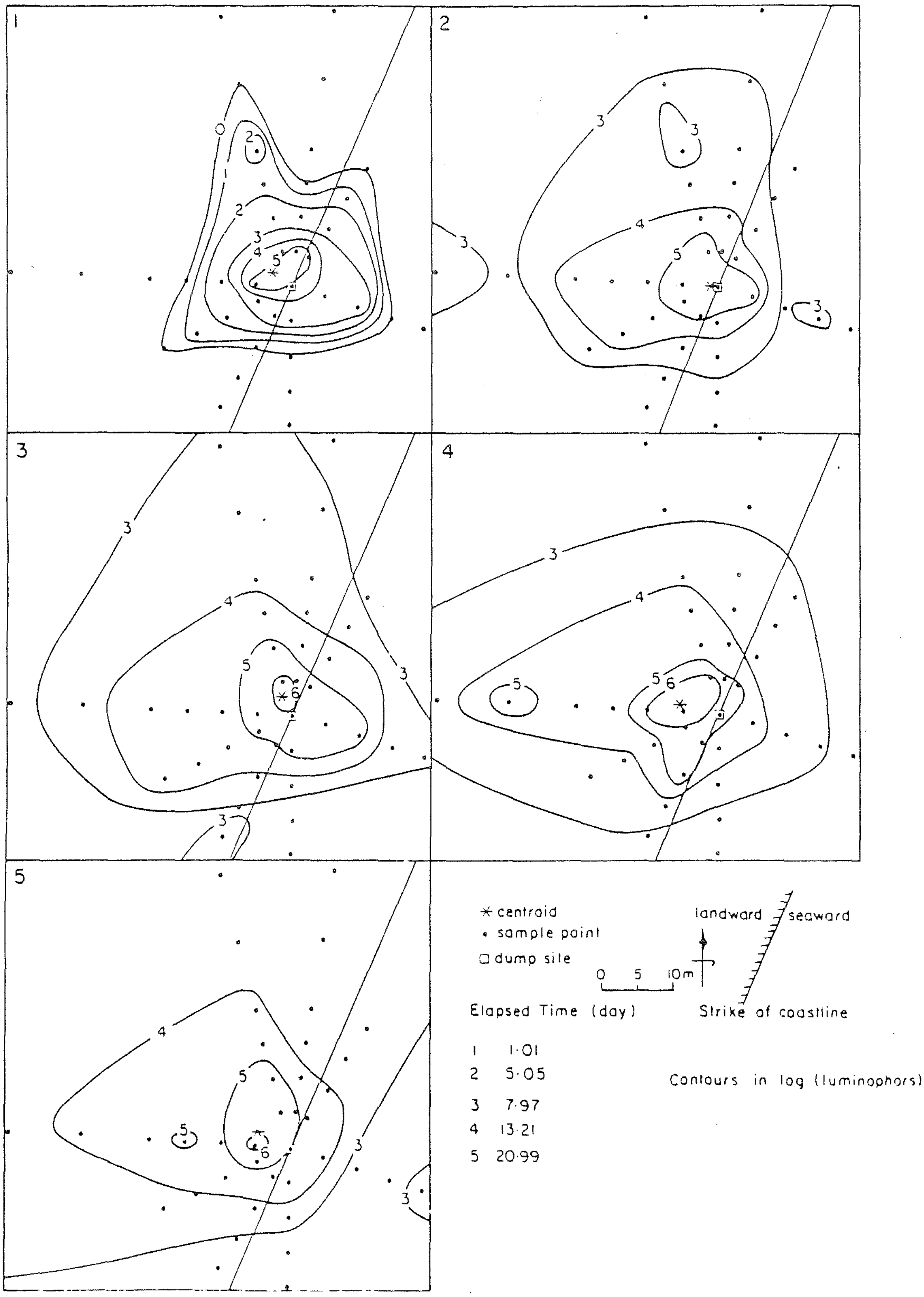


FIGURE 5.5 FLUORESCENT TRACER DISPERSION PATTERNS FOR EXPERIMENT 2.

Figure 5.6 shows movement of the tracer centroid over time.

Figures 5.5 and 5.6 show that the movement of the tracer over time was quite variable but that the net movement was in a landward direction. A large landward movement of tracer occurring between sample runs 3 and 4 can be seen clearly in the dispersion patterns and in the centroid movement.

Figure 5.7 shows the measured depths of tracer mixing, to the nearest 0.01 m, for sample runs 4 and 5. The measured depth exceeded 0.10 m only in one sample from sample run 4 and two samples from sample run 5.

Time between sample runs, centroid displacement, average grain velocity V, thickness of the mobile layer E and sediment transport rate q are shown for each sample run in table 5.2. The transport rates for the first three sample runs can be considered as maximum values because the average mixing depth for sample run 4 was used and tracer mixing depth can initially be expected to increase with time. Average grain velocity ranged from 3.29 m day^{-1} for sample run 1 to 0.17 m day^{-1} for sample run 5. Sediment transport rates ranged from 0.113 m^3 m^{-1} day^{-1} for sample run 1 to 0.010 m^3 m^{-1} day^{-1} for sample run 5.

Values of the wave and wave-dependent parameters (defined in table 4.3) are shown in table 5.3 for the periods between each sample run. $\overline{H}_s$ ranged from 0.66 m for sample run 1 to 0.90 m for sample run 4. $\overline{T}_s$ ranged from 9 s for sample run 3 to 11 s for sample runs 4 and 5. The linear current, $\overline{U}_{max1}$, ranged from 24.5 cm s^{-1} for sample run 1

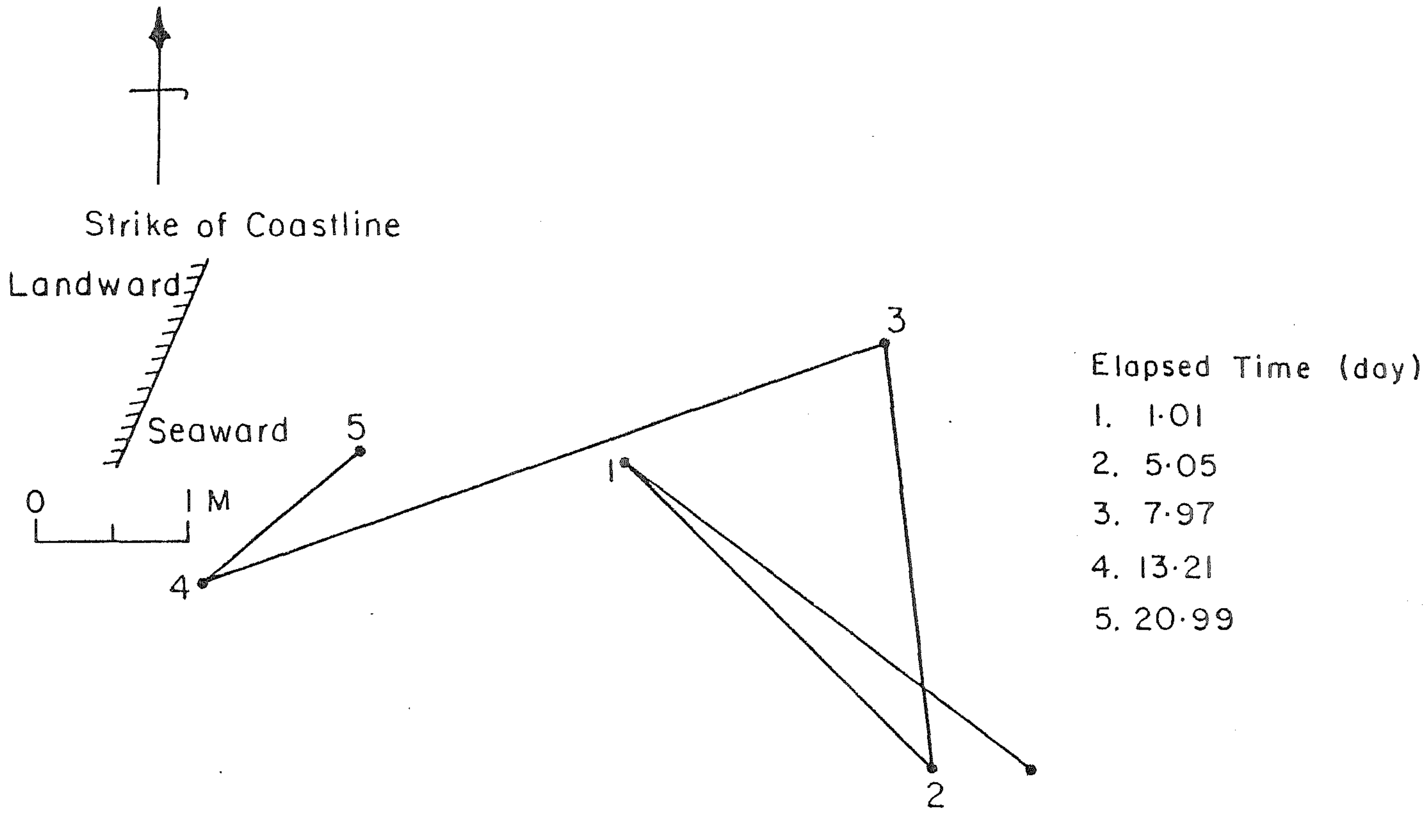


FIGURE 5.6 MOVEMENT OF THE TRACER CENTROID OVER TIME, EXPERIMENT 2.

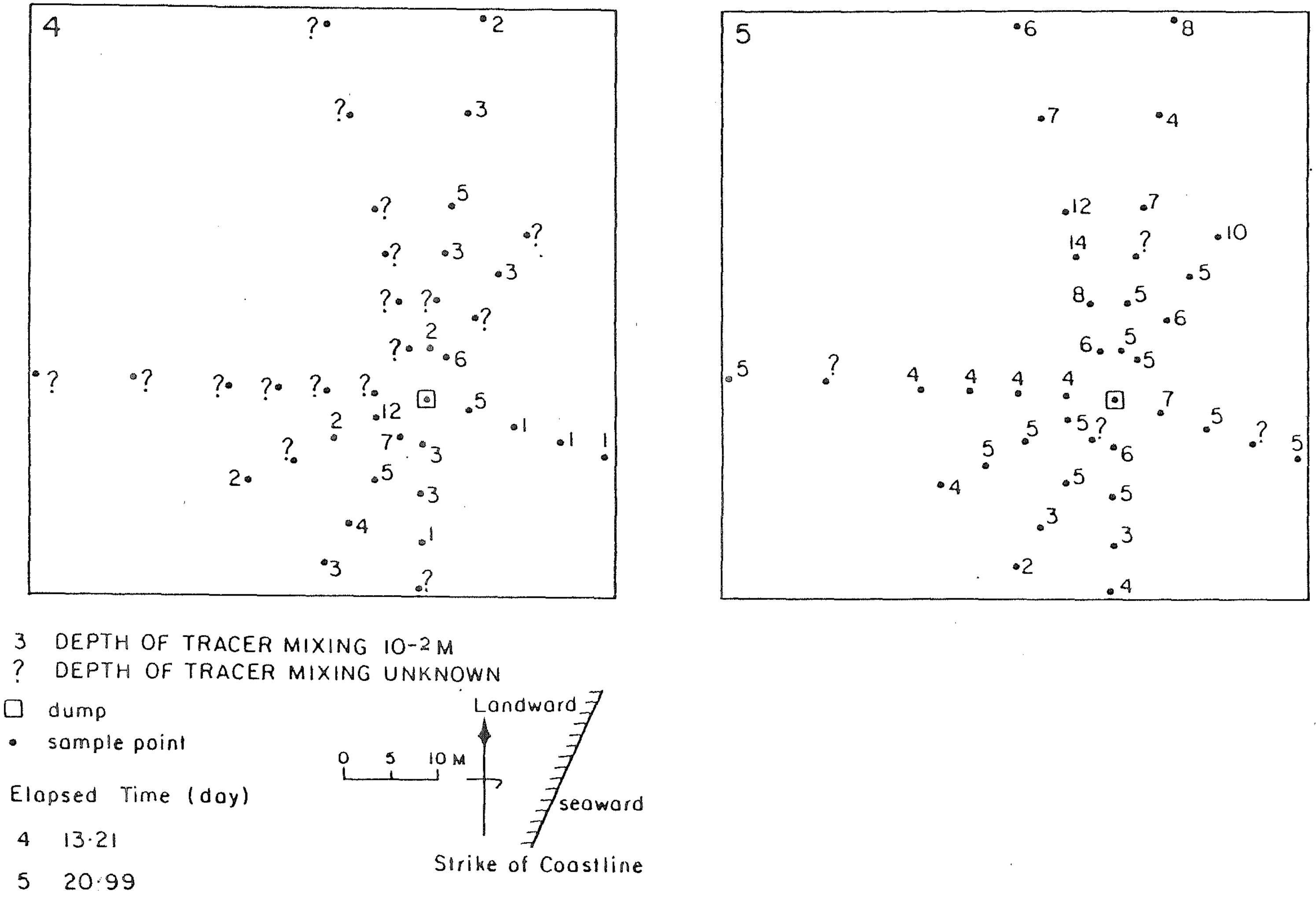


FIGURE 5.7 MEASURED DEPTH OF TRACER MIXING, EXPERIMENT 2.

TABLE 5.2 TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q FOR EXPERIMENT 2.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	DISPLACEMENT (m)	V MAGNITUDE ($m\ day^{-1}$)	V DIRECTION (°TRUE)	E (m)	q ($m^3\ m^{-1} day^{-1}$)
1	1.01	3.32	3.29	307	0.0345[1]	0.113
2	4.04	2.83	0.70	135	0.0345[1]	0.025
3	2.92	2.76	0.95	354	0.0345[1]	0.034
4	5.24	4.71	0.90	251	0.0345	0.032
5	7.78	1.35	0.17	51	0.0563	0.010

[1] Assumed from sample run 4.

TABLE 5.3 WAVE AND WAVE-DEPENDENT PARAMETERS FOR THE PERIOD BETWEEN EACH SAMPLE RUN, EXPERIMENT 2. PARAMETERS DEFINED IN TABLE 4.3.

PARAMETER	SAMPLE RUN NUMBER 1	2	3	4	5
$\overline{H}_s$ (m)	0.66	0.80	0.87	0.90	0.80
$\overline{T}_s$ (s)	10	10	9	11	11
$(\overline{H}_s)^2$ (m^2)	0.44	0.64	0.76	0.81	0.64
$\overline{H}_{rms}$ (m)	0.48	0.58	0.63	0.66	0.58
$\overline{H}_{max}$ (m)	1.01	1.18	1.49	1.36	1.26
$\overline{U}_{max1}$ ($cm\ s^{-1}$)	24.5	29.6	30.9	35.0	29.8
$\overline{U}_{max2}$ ($cm\ s^{-1}$)	0.6	1.1	0.9	1.9	1.4
$\overline{U}_{max3}$ ($cm\ s^{-1}$)	25.1	30.7	31.7	36.8	31.2
$\overline{U}_{max4}$ ($cm\ s^{-1}$)	23.9	28.5	30.0	33.2	28.4
PER (%)	100	100	100	100	100

to 35.0 cm s^{-1} for sample run 4. The calculated thresholds for the movement of very fine sand (table 3.10) were exceeded 100% of the time throughout the experiment.

The collection of wave direction data outlined in section 3.4.4.3 encompassed the present experiment and so it was possible to obtain some wave direction data. Figure 5.8 is a wave direction frequency diagram calculated from 15 daily observations. These observations represented 71.4% of the total number of days during which the experiment was running. Wave direction ranged from east-north-east to south-south-east with waves from the east being the most frequently occurring.

No significant relationships were found between average grain velocity or sediment transport rate and the wave or wave-dependent parameters. Initial transport of the tracer would have been enhanced because of the mound formed on the bottom when the tracer was released. For this reason the results from sample run 1 were removed and the regression analysis re-run. Again, no significant relationships were found. The main problem with the regression analysis was the lack of data points.

5.8 ADDITIONAL ANALYSIS

5.8.1 Index Of Net Movement

The index of net movement, θ, defined by Murray (1967) and described in section 4.7.3.2 was calculated for

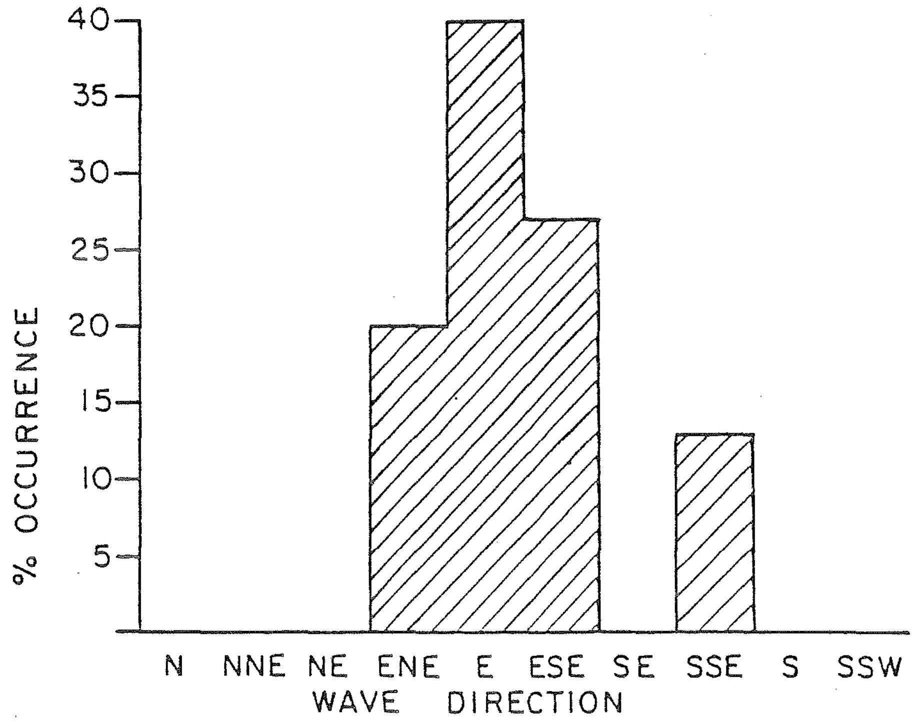


FIGURE 5.8 WAVE DIRECTION DURING EXPERIMENT 2. N = 15.

each sample run. The results are shown in table 5.4. All values of θ are in excess of 0.5 and therefore represent a net landward movement of tracer. The values range from 0.73 for sample run 3 to 0.97 for sample run 4.

TABLE 5.4 INDEX OF NET MOVEMENT, θ, FOR EACH SAMPLE RUN, EXPERIMENT 2.

SAMPLE RUN	θ
1	0.85
2	0.76
3	0.73
4	0.97
5	0.95

5.8.2 Tracer Accounting

A different accounting technique to that outlined in section 4.7.3.3 was used for this experiment because the total number of grains in each sample was known.

The first step was to calculate the total number of tracer grains released. This was calculated from the number of grains per gram and the total weight of tracer released. In section 4.7.3.3 four methods were used to estimate the total number of grains per gram for very fine sand. Three of these methods were based on dyed sand from Caroline Bay and it is these three that provide the best estimates for this experiment. The three estimated values of the number of grains per gram were each multiplied by 3.37×10^5g to give three estimates of the total number of tracer grains released. These estimates are given in table 5.5.

TABLE 5.5 ESTIMATES OF THE TOTAL NUMBER OF TRACER GRAINS RELEASED FOR EXPERIMENT 2.

TECHNIQUE[1]	GRAINS PER GRAM	TOTAL NUMBER OF GRAINS RELEASED
1	9.1×10^5	3.0×10^{11}
2	7.5×10^5	2.5×10^{11}
3	3.6×10^5	1.2×10^{11}

[1] Technique 1 used equation 4.8 and data from each fraction of a sieved sample. Technique 2 used equation 4.8 and the mean grain size for the sieved sample and technique 3 used counting of known dilutions to determine the number of grain per gram.

The next step involved calculating how many grains could be accounted for during each sample run based on the dispersion patterns. The following formula was used:

$$G_n = \sum_{i=1}^{n} (A_i \, 10^{(i+0.5)} / a_s) \qquad 5.2$$

where G_n = number of grains accounted for from the dispersio pattern

A_i = area contained in the i th contour (m^2)

a_s = area of one sample (m^2)

n = number of contours

The resulting values are shown in table 5.6.

TABLE 5.6 NUMBER OF GRAINS ACCOUNTED FOR FROM DISPERSION PATTERNS AND FROM THE DUMP AREA, AND THE PERCENTAGE OF THE TOTAL NUMBER OF GRAINS RELEASED THAT CAN BE ACCOUNTED FOR, EXPERIMENT 2.

SAMPLE RUN	NO. GRAINS FROM DISPERSION PATTERN	NO. GRAINS FROM DUMP	TOTAL NO. OF GRAINS	PERCENTAGE OF TOTAL RELEASED		
				3.0×10^{11}	2.5×10^{11}	1.2×10^{11}
1	0.013×10^{11}	0.46×10^{11}	0.47×10^{11}	15	19	39
2	0.052×10^{11}	0.55×10^{11}	0.60×10^{11}	20	24	50
3	0.130×10^{11}	1.01×10^{11}	1.16×10^{11}	39	46	97
4	0.256×10^{11}	1.27×10^{11}	1.53×10^{11}	51	61	128
5	0.091×10^{11}	0.79×10^{11}	0.88×10^{11}	29	35	73

It was obvious from the samples collected from the dump site that a considerable amount of tracer remained at the dump site throughout the experiment. It was therefore decided that this amount should be included in any accounting procedure. The total number of tracer grains present in each sample from the dump site was determined using the analysis procedure outlined in section 5.6. By assuming the dump site covered an area 2 m in radius (allowing for some radial spreading of the initial dump) the total number of tracer grains present in this area was calculated for each sample run. The resulting values are shown in table 5.6.

The total number of grains accounted for from the dispersion patterns and the total number present in the dump site were added for each sample run. This total was then divided by each of the three estimates of the total number of grains released to provide three estimates of the percentage of tracer that could be accounted for from each sample run. The results are shown in table 5.6. Using the estimate of 3.0 x 10^{11} grains released values ranged from 15% for sample run 1 to 51% for sample run 4. Using the estimate of 2.5 x 10^{11} grains released values ranged from 19% for sample run 1 to 61% for sample run 4. Using the estimate of 1.2 x 10^{11} grains released values ranged from 39% for sample run 1 to 128% for sample run 4. The higher the estimated number of grains released the lower the percentage accounted for. The fact that greater than 100% of the tracer release was accounted for on one occasion is simply a reflection of inaccuracies in the accounting procedure.

5.8.3 Regression Analysis Of Combined Data

Data from this experiment were combined with the data for very fine sand from experiment 1 so that further regression analysis could be undertaken. The analysis was carried out to look for relationships between average grain velocities or sediment transport rates and the four horizontal oscillatory current parameters defined in table 4.3. The reason why these current parameters were used is that water depth is incorporated in their calculation which eliminates any effects arising from combining data from experiments in different water depths.

No significant relationships were found using the combined data so it was split into two groups. The first group contained data from the initial period of tracer movement and included sample runs 1 - 4 from experiment 1 and sample run 1 from the present experiment. The second group contained the data obtained after initial mixing had occurred (at least 5 days following the release) and included sample runs 5 - 7 from experiment 1 and sample runs 2 - 5 from the present experiment. Again no significant relationships could be found. This may be due to the complex nature of the sediment transport process. Other possible reasons why no relationships could be found include the following:

1. The current velocities used in the analysis were calculated from linear (Airy) wave theory and Stokes' second order wave theory using average wave conditions. Results from a limited number of current measurements described in section 3.4.4.2 suggested that the linear theory may overestimate the actual current velocities.

2. The number of data points was very limited.

3. Only the magnitudes of the average grain velocities and sediment transport rates were used and no account was taken of the direction of movement.

5.9 DISCUSSION

5.9.1 Tracer Sand

The tracer sand used for this experiment was coarser than the native seafloor sand at the experiment site. Approximately 75% of the seafloor sand fell within the size range covered by the tracer sand and it is therefore this fraction to which the results apply.

It is not known what influence the differently sized native sediment had on the transport of the tracer sand. Cook (1969) and Cook and Gorsline (1972) found that when ripples were present all sand sized particles could be moved with equal facility. Because ripples existed throughout the present experiment and because the difference in grain size between the tracer sand and the seafloor sand was relatively small (0.38 ϕ difference in mean grain size) the grain size difference is unlikely to have had a major affect on the transport of the tracer sand.

5.9.2 Dispersion Patterns And Centroid Displacement

The dispersion patterns in figure 5.5 show a net landward movement of tracer sand. This was confirmed by the index of net movement which was calculated for each pattern. The highest index calculated was 0.97 for sample run 4 which indicates a very strong tendency for landward movement of tracer sand. The lowest calculated index was 0.73 for sample run 3 which indicates a strong tendency for landward movement of tracer sand. All patterns, therefore, indicated a clear dominance of landward movement over seaward movement.

All of the dispersion patterns, with the exception of sample run 4, showed a pronounced northward movement of tracer sand superimposed on the net landward movement. Figure 5.8 shows that wave direction, measured on 15 days during the experiment, ranged from east-north-east to south-south-east. The net landward movement of tracer sand was probably a response to waves from the east and east-south-east, while the northward movement was probably due to waves from the south-south-east.

Figure 5.6 shows that the displacement of the tracer centroid was quite variable, sometimes moving landward and sometimes seaward. The maximum displacement from the dump was 5.5 m for sample run 4. For the period between sample run 2 and sample run 3 there was a clear northward movement of tracer sand.

One possible cause for the variable movement of the centroid may be burial of the tracer. Blackley (1980) points out that buried tracer, if uncovered, may act as a new source of tracer material and, if the concentration is high, may cause an apparent movement of the centroid toward the new source. For the present experiment it is known that large amounts of tracer remained buried at the dump ground throughout the experiment (see later). If this material was ever exposed it could have acted as a new injection of tracer and thereby caused an apparent movement of the tracer centroid back towards the dump. This could explain the movement of the centroid from sample run 1 to sample run 2.

5.9.3 Thickness Of The Mobile Layer

Figure 5.7 shows the measured depths of tracer mixing for sample runs 4 and 5. There are quite a number of missing values and all but five of these were due to loss of, or contamination within the core. The other five were simply the first few samples from sample run 4 which were bagged before it was decided to inspect each sample for the depth of tracer mixing. One possible way to improve on the recovery of samples would be to use clear plastic core tubes so that once the sample had been taken and returned to the surface it could be inspected. If it was found to be unsatisfactory it could be re-taken immediately. Clear plastic core tubes have been used by Gaughan (1979) and Kraus, Farinato and Horikawa (1981).

Komar *in* Blackley (1980, p. 11) suggests that the depth of tracer mixing is likely to decrease with distance away from the dump site. Figure 5.7 shows that this was generally the case for the available data for sample run 4 but that this was not the case for sample run 5 where in many cases the depth of mixing increased away from the dump. Alternatively, where a decrease occurred it was relatively small. This implies that the mixing of tracer sand within the mobile layer was more complete for sample run 5 than for sample run 4. It also indicates that the pattern of mixing suggested by Komar *in* Blackley (1980, p. 11) may occur initially but if sufficient time is allowed the depth of mixing may become more evenly distributed within the tracer cloud.

The depths of tracer mixing shown in figure 5.7 were averaged for both sample runs and the average value was taken as a measure of the thickness of the mobile layer which was then used in the calculation of sediment transport rates. The transport values were therefore calculated from the maximum depth of tracer mixing whereas for experiment 1 a concentration weighted depth was used.

Gaughan (1979) compared three different estimates of the thickness of the mobile layer. One estimate was based on the observed maximum depth of tracer grains within a core while the other two estimates were based on concentration weighting procedures. Gaughan found that the estimates differed by less than 10%. He therefore concluded that the estimate based on the maximum depth of tracer mixing was a suitable value to use.

Inman et al. (1981) also tested three different measures of the thickness of the mobile layer. They calculated a concentration weighted depth, a depth based on a cut-off concentration of 1 grain per gram, and the maximum depth of tracer mixing. The longshore variation of these values from the tracer injection line was plotted. The values ranged from 0 - 9 cm and the relationship between them alongshore was variable. The maximum mixing depth was found to be on average 2.1 times greater than the concentration weighted depth and 3.9 times greater than the cut-off concentration depth (ignoring the two cases where the maximum depth equalled 1 cm and the cut-off concentration depth equalled 0 cm).

There is therefore some uncertainty as to whether or not the maximum depth of tracer mixing provides a good estimate of the thickness of the mobile layer. However, it is certain that any calculated sediment transport rate based on the maximum depth of mixing should set an upper limit to the possible range of values. Therefore, because the maximum depth of tracer mixing was the only value measured for this experiment, calculated transport rates can be considered to be maximum values.

5.9.4 Sediment Transport Rates

The calculated sediment transport rates for this experiment ranged from 0.113 $m^3\ m^{-1}\ day^{-1}$ for sample run 1 to 0.010 $m^3\ m^{-1}\ day^{-1}$ for sample run 5. The rates compare well with those given in table 4.4 for very fine sand for experiment 1.

The initial rates of tracer movement for sample runs 1 - 4 of experiment 1 and for sample run 1 of the present experiment are an order of magnitude higher than the rates calculated during the latter parts of the experiments. The reason for this has been discussed previously and relates to the mounds formed on the seabed during the tracer releases.

Wave height during this experiment was lowest for the period between the dump and sample run 1, with $\overline{H}_s$ = 0.66 m and $\overline{T}_s$ = 10 s. For the remainder of the experiment wave height was relatively constant with $\overline{H}_s$ ranging from 0.80 - 0.90 m and $\overline{T}_s$ ranging from 9 - 11 s. Wave height was below the average calculated for the full set of wave data ($\bar{H}_s$ = 0.97 m) and therefore longer term transport rates would probably be higher than the calculated values.

5.9.5 Tracer Accounting

Two main points emerge from the tracer accounting procedure. Firstly, there is a considerable amount of uncertainty in the procedure itself; and secondly, a considerable amount of tracer remained at the dump site throughout the experiment.

The uncertainty in the accounting procedure begins with the estimated total number of grains released, which varies according to the estimated number of grains per gram. Table 5.5 shows that the three values used for the experiment give significantly different estimates of the total number of grains released. The estimated number of tracer grains that could be accounted for from the dispersion patterns assumed that the tracer concentration between contour lines was equal to the geometric mean of the contour values. There is no way of checking the validity of this assumption. The estimated number of grains remaining at the dump on each sample run was based on one sample from the dump site. This sample was taken to be representative of the dump site which was assumed to be 2.0 m in radius. The choice of 2.0 m for the radius of the dump site had a major influence on the estimated total number of grains remaining at the dump site. Obviously more cores taken in the immediate vicinity of the dump site would have improved these estimates. They would, however, also have added to the time required for sampling and analysis.

The fact that for one estimate of the total number of grains released the percentage of tracer accounted for exceeded 100% on one occasion confirms the uncertainty that exists within the accounting procedure.

Examination of table 5.6 shows that a considerable amount of tracer remained at the dump site throughout the experiment. Despite the uncertainties mentioned above, the calculated amount of tracer remaining at the dump site was in all cases an order of magnitude higher than the amount accounted for from the dispersion patterns. This could be a function of the lower than average wave energy conditions that occurred during the experiment. It could also indicate that more tracer was released than was required. It must be remembered, however, that this experiment was ended prematurely when a fishing boat ran over the grid and that increased wave activity may have released this material had the experiment lasted longer. A check on the recorded wave data showed that within 5 days of the final sample run the significant wave height exceeded 2.0 m continuously for a 12 hour period.

Other tracer studies have also found that high concentrations of tracer have remained at the dump site throughout the experiment. Zenkovitch (1960) noted that despite observing high sand transport velocities fluorescent tracer sometimes remained for long time periods at a dump site. In a fluorescent tracing study in Botany Bay, New South Wales, Moore and Fry (1967) found that high concentrations of fluorescent tracer remained at several dump sites for a period of nearly 6 months. During respective radioactive tracer studies Courtois and Monaco (1969) and Rohde (1977) found that activity remained high in close proximity to the dump point. Komar in Greer and Madsen (1979, p. 1573) found that during a fluorescent tracer experiment an area of high concentration remained at the point of injection.

5.10 CONCLUSIONS

Tracer dispersion patterns from this experiment suggest that very fine sand on the seafloor immediately to the south of Timaru Harbour entrance channel moves both landward and northward. Calculated transport rates ranged from 0.010 - 0.113 $m^3\ m^{-1}\ day^{-1}$ which compare well with the rates obtained for very fine sand at a site further north. Variability in the tracer centroid movement may have been due to re-excavation of buried tracer.

The calculated transport rates are thought to be maximum values for the wave conditions occurring throughout the experiment because they were based on average values of the maximum depth of tracer mixing. This effect would be heightened for the first three sample runs because the depth of mixing from sample run 4 was used for the transport calculations. Wave conditions throughout the experiment were, however, below the recorded average for the full set of wave data and so in the long-term rates may be slightly higher.

When regression analysis was used to look for significant relationships between average grain velocity or sediment transport rate and calculated horizontal oscillatory current parameters, using data from this experiment and experiment 1, no significant relationships could be found. This may be a reflection on the data used in the analysis. However, it may also be due to the complex nature of the sediment transport process.

Although no measurements of the depth of tracer mixing were obtained for the first three sample runs the information obtained for the final two sample runs was greatly improved from that obtained during experiment 1. The improvement arose through the use of pistons in the sample tubes which enabled all samples to be retained intact. The distribution of the mixing depth around the dump site suggested that initially mixing depth will decrease with distance from the dump site but as time increases a more uniform distribution will occur.

The accounting procedure showed that a considerable amount of tracer remained at the dump site throughout the experiment. Because tracer concentrations in the grid samples were sufficient it would appear that the material remaining at the dump site was superfluous. Therefore more tracer may have been released than was required for this experiment. The determination of initial tracer quantities is considered further in chapter 8.

CHAPTER VI

FLUORESCENT TRACING OF COARSE SEDIMENT AT THE SHELF/BEACH INTERFACE

6.1 INTRODUCTION

The supply and loss of sediment to and from a beach can be viewed in terms of a budget, where sources of sediment are credits and losses of sediment are debits. If credits exceed debits there will be a net excess of sediment and the beach will accrete; if debits exceed credits there will be a net loss of sediment and the beach will erode; and, if credits equal debits there will be no net change in the sediment volume and the beach will be stable. Table 6.1 lists the possible sources and sinks (losses) of sediment for a littoral zone sediment budget. This chapter is concerned with sediment transport from the offshore as a possible source of beach sediment.

Onshore transport of sediment from the seafloor can arise in two distinctly different ways. Firstly, in the long-term there may be a net gain of sediment on the beach resulting from the onshore movement of sediment from the continental shelf. Secondly, in the shorter term, sediment may move onshore following seasonal or storm-induced beach profile changes. Sediment budgets are normally calculated for the long-term and so the short-term onshore movement in response to profile changes is excluded from further consideration here.

TABLE 6.1 SOURCES AND SINKS FOR A LITTORAL ZONE SEDIMENT BUDGET (ADAPTED FROM U.S. COASTAL ENGINEERING RESEARCH CENTER 1977, TABLE 4-13, P. 4-118).

SOURCES	SINKS
Offshore shoal or island	Submarine canyon
Rivers, streams	Inlets
Renourishment	Mining, extractive dredging
Longshore transport into area	Longshore transport out of area
Sediment transport from the offshore	Sediment transport to the offshore
Coastal erosion, including erosion of cliffs and dunes	Overwash. Coastal land and dune storage
Beach erosion	Beach storage
$CaCO_3$ production	$CaCO_3$ losses

The role of supply of sediment from the offshore is difficult to determine accurately and is generally an unknown component in the sediment budget (Bowen and Inman 1966; Komar 1976, p. 237). Its contribution to the sediment budget will depend on the location but in general the contribution is either negligible or of minor importance relative to other components of the budget (Trask 1952; Johnson 1959; Caldwell 1966; Komar 1976, p. 237; U.S. Coastal Engineering Research Center 1977, p. 4-121). There is, however, evidence of an offshore source in some localities and some examples are given below.

Saville (1961) found that volumetric measurements of accretion on the east side of Fire Island and other jetties in the New York area, and erosion rates of various beaches indicated an annual littoral drift rate of 344 000 m^3 yr^{-1}. Measurement of the erosion rates in the supply areas indicated that substantially less sand was supplied than was accreting and so it was postulated that some portion of the littoral drift had its origins in offshore sources.

Bowen and Inman (1966) calculated a sediment budget for the beaches in the vicinity of Point Arguello, California. They found a net deficit of sediment in one area of 76 500 m^3 yr^{-1} which must have been balanced either by transport of sand from the shelf or by longshore transport around Point Buchan. Profile data showed that the shelf had eroded an amount more than sufficient to supply the required material and they considered this the more important source.

Pierce (1969) calculated a sediment budget for the section of barrier island shoreline between Hatteras Inlet and Cape Lookout, North Carolina. He found that the accretion rate of 796 000 m^3 yr^{-1} required an input greater than can normally be supplied by the commonly assumed sources such as longshore drift and transportation from the mainland. Pierce believed that the continental shelf supplied the material required to balance the budget.

Giles and Pilkey (1965) studied heavy mineral distributions in the Atlantic beach and dune sediments of the southern United States. Evidence from the heavy mineral distributions indicated that beach and dune sediments in the area were derived in part from sediment deposited on the adjacent shelf and in part from local rivers. The problem with evidence from mineralogical studies such as this is that it is not clear when the sediment moved onshore from the shelf or whether the onshore movement is still active today.

Pilkey and Field (1972) found that oolitic grains in central Florida beach sands and phosphorite grains on North Carolina beaches could only be derived from the continental shelf, therefore indicating onshore transport in these places. The shelf-derived oolite grains are easily abraded and therefore their presence in quartz beach sands was taken as evidence of contemporary onshore transport.

Dingwall (1974) studied the bay-head sand beaches of Banks Peninsula, N.Z. Evidence from sediment textures and mineralogy suggested that some of the beaches that were accreting derived a portion of their sand from longshore-drifted sediment on the adjacent continental shelf.

Post-glacial progradation at Kaipara Barrier, North Island, N.Z., was studied by Schofield (1975). He found that the late post-glacial input of sand from landward sources could account for less than 7% of the total volume of deposited sand. The only other possible source was the seafloor, therefore indicating onshore transport.

Four rapidly prograding sand beaches along the north-eastern flank of Otago Peninsula, N.Z., were studied by Nicholson (1979). He found that the entire sand sequence could have accumulated within the last 200-500 years. Because the beaches were isolated from active river sources Nicholson concluded that the sand must be derived from the continental shelf.

Thoms (1981) analysed sediment texture and rollability to help determine sedimentation patterns in the New River Estuary, Southland, N.Z. Results from the analysis identified the adjacent continental shelf as the dominant external source of medium-fine sand, therefore indicating onshore movement.

Further data on the onshore movement of sediment from the continental shelf can be obtained from reports of beach renourishment operations that have utilised offshore dumping. In 1935 2 717 000 m^3 of sand was deposited offshore from a beach at Atlantic City, New Jersey, in 4.6 - 6.0 m of water. The operation was observed closely and no measurable quantity of material was found to have moved onto the beach (Hall and Watts 1957).

In another renourishment operation in 1935 153 000 m^3 of sand was placed in 6.7 m of water at Santa Barbara, California. The sand formed a mound approximately 670 m long and 1.5 m high. Surveys carried out 9 years later showed no significant change in the mound thus indicating that no significant transport had occurred (Wiegel 1964; Walton and Purpura 1977; Schwartz and Musialowski 1980).

In 1948 at Long Beach, New Jersey, dredged material was placed in a ridge 2.1 m high, 1130 m long and 230 m wide in 10 - 12 m of water. The area was surveyed over a 4 year period and results showed no evidence of a shoreward movement of material (Hall and Herron 1950; Harris 1954).

At Copacabana Beach, Brazil, 2 000 000 m^3 of sand was dumped in 4.6 - 5.8 m of water during 1969-70. Sand was also pumped directly onto the beach, which, within a 2 year period following completion of the operation, had increased in width by an amount that corresponded well to the total placement offshore plus that directly placed on the beach (Vera-Cruz 1973; Walton and Purpura 1977).

Two successful offshore renourishment operations were carried out in 1976, one at the Limfjord Barriers, Denmark, and the other at New River Inlet, North Carolina. The dumped sand formed offshore bars which in both cases migrated up onto the beach (Mikkelsen 1977; Schwartz and Musialowski 1980).

In 1979 95 000 m^3 of sand was dumped in 5 m of water, or deeper, at Tarakohe, N.Z. The tidal range in this area is 4.0 m and all sand was dumped at high tide. Surveys 8 months after the completion of dumping indicated that 43 000 m^3 of sand had come ashore and the process was considered to be incomplete at that stage (Dr R M Kirk, Department of Geography, University of Canterbury 1981, pers. comm.).

The evidence provided by the successful renourishment operations does not clearly point to an overall onshore movement of sediment from the continental shelf but may simply represent short-term profile adjustments such as those that occur following storm events. However, the earlier examples show clearly that no movement occurred from the deeper water depths. One factor common to the most successful offshore renourishments was that the dumped sediment was coarser than the native beach sediment at the site. In view of this and the theories of Cornish (1898) and Cornaglia in Zenkovich (1967, p. 101), outlined in section 1.3, it can be argued that the onshore supply of sediment from the continental shelf may depend on the relative grain sizes of the shelf and beach sediments.

All of the evidence presented so far for an offshore source of sediment has been concerned with sand beaches. The best evidence concerning an offshore source for coarse grained beaches comes from sediment tracing experiments, the work of Kidson and Carr (1959) being particularly relevant. Kidson and Carr carried out a radioactive pebble tracing experiment on the seabed at Orfordness, Suffolk, U.K., to try and obtain data on the extent to which sediment passed between the seabed and the shingle beaches of a large shingle spit. The two innermost experimental sites were 203 m and 213 m offshore respectively. Although landward movement of pebbles at these sites was recorded Kidson and Carr were quite certain that no material reached the shore. They concluded that no transfer of beach material between the offshore zone and the shore could take place in the area except possibly under the most severe conditions. They believed that movement of material between the beach and the seabed is confined to a narrow zone immediately offshore.

Other studies have also shown a landward movement of pebbles on the seafloor (Steers and Smith 1956; Crickmore, Waters and Price 1973), but whether or not these pebbles ever reach the coast is not known.

Onshore transport of sediment is only likely to occur if a source area lies within the zone of significant sediment transport and is most likely to be significant if the source area is located within the very active littoral transport zone. Using the technique of Hallermeier (1981a,b) it was shown in section 3.6.1 that at Timaru the zone of significant sand transport extended out to the 37 m isobath and that the very active littoral zone, independent of sediment size, extended out to the 7 m isobath. Figure 3.4(a) shows that there are some patches of gravel on the seafloor in the study area and at least some parts lie within the very active littoral zone. Figures 4.6 - 4.10 show that coarse sediments moved in a landward direction at a position 1.4 km offshore during experiment 1. If these coarse sediments continued to move towards the shore, would they be deposited on the mixed sand and gravel beaches? In order to investigate the possibility of such a transfer occurring a fluorescent tracing experiment, referred to as experiment 3, was planned and executed. The remainder of this chapter is devoted to outlining the experiment and its results.

6.2 AIMS

The experiment had the following aims:

a) To see if sediment could travel from a position on the nearshore seabed to the foreshore of a mixed sand and gravel beach (see fig. 2.3). Note firstly that this does not involve measuring the rate of transfer; and secondly, that the movement is to the foreshore of the beach so that any transfer to other parts of the beach will not be recorded. The reason why only the foreshore is included is outlined in section 6.7.

b) To assess the wave conditions under which such movement did or did not take place.

c) If movement did occur, to compare any longshore component with longshore current observations made during the experiment.

d) If movement did occur, to investigate the influence of particle shape on transport behaviour. The significance of this will be outlined in detail in the following section.

6.3 THE ROLE OF PEBBLE SHAPE

Several workers have observed a shore-normal sorting of beach pebbles with respect to shape, with flatter pebbles concentrating on the landward side of the profile and spherical pebbles occurring on the seaward side of the profile (see for example Landon 1930; van Andel, Wiggers and

Maarleveld 1954; Flemming 1964; Bluck 1967). This type of sorting was observed by the author at South Beach, Timaru, while diving to inspect the nearshore face of a mixed sand and gravel beach. Pebbles on the lower section of the nearshore face were observed to be considerably more spherical than those commonly seen on the foreshore of the beach. No sample was collected to test the validity of this observation. Another dive was made in the area at a later date and on this occasion a sample was collected 5 m up from the base of the nearshore face. A second sample was collected from the foreshore of the beach so that a comparison could be made between pebbles on the foreshore and those on the nearshore face. These samples were analysed in the following way:

1. They were washed, to remove any organic matter or extraneous material, and then air dried.

2. Each sample was then hand sieved into five groups - >9.5 mm, 8.0 - 9.5 mm, 6.7 - 8.0 mm, 5.6 - 6.7 mm and <5.9 mm in median diameter.

3. The material less than 5.6 mm diameter was discarded because of the difficulty of measuring the shape of smaller particles.

4. Fifty pebbles were systematically selected from each remaining size group for each sample.

5. The major (a), intermediate (b) and minor (c) axes of each selected pebbles were measured with callipers and recorded.

A computer program was then written to:

1. Classify each pebble as a sphere, disc, rod or blade according to the classification of Zingg *in* McLean

(1982, p. 885). The classification is:

a) Spheres $b/a > 0.67$; $c/b > 0.67$

b) Discs $b/a > 0.67$; $c/b < 0.67$

c) Rods $b/a < 0.67$; $c/b > 0.67$

d) Blades $b/a < 0.67$; $c/b < 0.67$

2. Calculate for each pebble the sphericity index ψ of Krumbein (1941).

$$\psi = \sqrt[3]{bc/a^2} \qquad 6.1$$

3. Determine the number of spheres, discs, rods and blades and the average value of ψ for each 50 pebble subsample.

The results from this analysis are presented in table 6.2. The number of spheres, discs, rods and blades and the average ψ value is given for each size group for each sample. The table also gives the total number of spheres, discs, rods and blades in each sample and the relative percentage of each type, along with the average value of ψ for each sample.

The results confirm the observation of greater sphericity of pebbles on the nearshore face than on the foreshore of the beach. The percentage of spheres in the sample from the nearshore face was four times greater than the percentage found in the foreshore sample. The nearshore face sample also contained a greater percentage of rods, but a lesser percentage of discs or blades than the foreshore sample. Krumbein's sphericity index ranges from 0 to 1, with a true sphere having a value of 1. A 't' test on all size groups showed that at the 1% significance level the index

	MEDIAN DIAMETER											
	>9.5 mm		8.0 - 9.5 mm		6.7 - 8.0 mm		5.6 - 6.7 mm		Total No. and Average Value		Percentage of total sample	
	Fore-shore	Near-shore Face	Fore-shore	Near-shore Face	Fore-shore	Near-shore Face	Fore-shore	Near-shore Face	Fore-shore	Near-shore Face	Fore-shore	Near-shore Face
Spheres	1	11	4	16	4	23	10	29	19	79	9.5	39.5
Discs	36	26	28	19	28	18	25	13	117	76	58.5	38.0
Rods	0	8	4	9	7	6	7	7	18	30	9.0	15.0
Blades	13	5	14	6	11	3	8	1	46	15	23.0	7.5
Krumbein Sphericity	0.64	0.71	0.63	0.71	0.64	0.74	0.68	0.75	0.65	0.73		

TABLE 6.2 PEBBLE SHAPE ON THE FORESHORE AND THE NEARSHORE FACE AT SOUTH BEACH

was higher for the subsamples from the nearshore face than for the subsamples from the foreshore. This therefore indicates a higher pebble sphericity on the nearshore face and concurs with the finding of more spherical pebbles there.

Two possible explanations exist to explain the observed sorting pattern. Firstly, Landon (1930) believed that flat pebbles move by "skidding" while spherical pebbles move by rolling. Flat pebbles move up and down the beach in response to the swash and backwash. Spherical pebbles, however, move up the beach in response to the swash but, because they tend to roll, move relatively greater distances down the beach in response to the backwash. In this way the flatter particles remain on the beach while the spherical particles move down into deeper water. Secondly, Bluck (1967) proposed that disclike pebbles were more easily lifted from the seafloor than sperical pebbles of the same median diameter because of their lighter weight, and, once in suspension, the discoidal pebbles travel further because they have a lower settling velocity (Krumbein (1942) found that discs have the lowest settling velocity of any particle shape). Both explanations seem likely and it is probably some combination of the two that produced the pattern that was found.

The present experiment provided an opportunity to obtain further information with respect to shape sorting on the profile. If the tracer sediment used in this experiment was selected so that it encompassed the full spectrum of pebble shapes then any trend in the shape of tracer pebbles found on the foreshore of the beach could be attributed to selective sorting across the profile.

6.4 LOCATION OF THE EXPERIMENT

The barrier beach enclosing Washdyke Lagoon was chosen as the site for experiment 2 (see fig. 3.8). As outlined in section 2.2 the beach at Washdyke is under-nourished and eroding rapidly. The experiment would enable an assessment to be made as to whether this beach could receive nourishment from the seafloor. The tracer dump site was located 100 m seaward of a marker on the beach which was 500 m south of the Timaru city sewer outfall. The water depth at the site was approximately 3 m.

6.5 PREPARATION OF FLUORESCENT TRACER

It was decided to use only sediment coarser than coarse sand for this experiment because it was thought that detection of any finer sediment would not be possible on the foreshore of the beach. The maximum sediment size was set at 38.1 mm median diameter.

Sediment for dyeing was obtained from South Beach because it was more accessible than the beach at Washdyke. Approximately half of the sediment used was obtained from the foreshore of the beach with the other half being obtained from the nearshore face. To obtain the sediment from the nearshore face the author and another diver worked from a small boat just offshore from the beach. Tins were taken to the bottom, filled with gravel, and then air-lifted to the surface where they were loaded aboard the boat.

Because sediment was obtained from both the foreshore and the nearshore face it was possible to assume that the tracer would contain the full spectrum of particle shapes that occurs on the mixed sand and gravel beaches in the study area.

All sediment was returned to the Physical Laboratory, Department of Geography, University of Canterbury where it was dyed with a fluorescent pigment using the technique described in section 4.3.2.

Samples of the fluorescent dyed sediment were taken and sieved so that the amount of sediment falling into a number of size classes could be determined. The size classes and the results are given in table 6.3.

TABLE 6.3 QUANTITIES OF FLUORESCENT DYED SEDIMENT FOR EXPERIMENT 3.

GRAIN SIZE (MEDIAN DIA. MM)	SIZE CLASS	AMOUNT (kg)
4.0 - 38.1	Pebbles	389
2.0 - 4.0	Granules	94
1.0 - 2.0	Very Coarse Sand	18
0.5 - 1.0	Coarse Sand	27
	TOTAL	528 kg

6.6 RELEASE OF TRACER MATERIAL

The fluorescent tracer was placed in tins in lots of approximately 20 kg which were loaded aboard two small boats. No pre-wetting was necessary because only coarser-sized sediments were used. The boats proceeded to the dump site where one of them anchored, letting out its anchor line until it was opposite the marker on the beach. This probably gave a longshore position accurate to within ± 5 m. All tins were eventually transferred to this boat for release.

Because of the coarse nature of the tracer it could have been released by direct tipping from the boat without fear of it being transported any great distance in suspension before reaching the seafloor. However, because divers were available they were used to carry the tins to the bottom and release the tracer. All of the tracer was released within 30 minutes and it formed a mound on the bottom approximately 2 m in diameter and 10 - 15 cm high.

The seabed at the dump site consisted of a 10 - 15 cm thick layer of very fine sand (mean grain size 3.33 ϕ) with some intermixed pebbles, overlying a yellow mud material. Despite the limited water visibility (less than 20 cm) the author inspected the seafloor landward of the dump site up to the break point on the beach. The sand layer seemed slightly thicker inshore from the dump site and only rare patches of gravel were encountered on the way to the break point. The submarine profile of the beach appeared to be quite different from that previously described in section 2.2

for South Beach. The most striking difference was the narrow width of the beach at Washdyke in comparison with South Beach. This was a function of the volume of gravel in the beach which at Washdyke appeared to be very much less than at South Beach. This is not surprising because the beach at Washdyke is severely undernourished while the beach at South Beach has accreted as northward moving gravel is trapped by the Eastern Extension Breakwater. The profile at Washdyke did not appear to be as steep as that at South Beach and the sharp cut-off point marking the seaward limit of gravel, and the associated change in gradient, were not found at Washdyke, possibly because they occurred landward of the area inspected by the author. This could not be confirmed at the time because turbulence prevented inspection of the profile landward of the break point.

No subsequent checks on the dump site were made because of the difficulty of diving in this area and because it would have been difficult to maintain a buoy marking the exact dump site.

6.7 SEARCHING FOR TRACER MATERIAL

In section 6.2 it was stated that one aim of this experiment was to see if sediment could travel from the nearshore seafloor to the foreshore of the beach. It was noted that this meant a transfer of sediment to the beach could occur undetected if the sediment did not move to the foreshore of the beach. In view of the fact that this experiment was designed to investigate the supply of offshore sediment to the beach as a whole, this introduced a severe experimental limitation. However, due to the high energy environment existing at the site it was impracticable to consider using divers or boats for searching or sampling either the seabed inshore from the dump site or the nearshore face. Searches were therefore limited to the foreshore. Carr (1971) also noted the impracticability of diving or boat searches close inshore near a high energy pebble beach.

Searches for the fluorescent tracer on the foreshore were of two kinds. Firstly, night time searches were undertaken with a portable UV light and, secondly, daytime visual searches were made by treating the tracer as though it was simply a coloured tracer. Night time searches for fluorescent tracer have been employed by Reid and Jolliffe (1961), Russell (1961) and Joffiffe (1964). Daytime visual searches for coloured tracers have been employed by Jolliffe (1964), Gleason, Blackley and Carr (1975) and Caldwell (1983). Both methods search only the surface of the beach.

Four night time searches and 11 daytime searches were made over a period of 2.2 months following the dump. Of these, 11 were made at low tide, three at high tide and one at half-tide. A previous search before the dump had shown that no native beach material could be confused with the tracer material.

Initially it was planned to use a quadrat when searching but this was abandoned on the first search because not enough beach could be covered. Instead searches involved walking back and forth along the beach parallel to the water line, starting at the seaward side of the profile and working progressively up the beach. Footprints in the gravel were used to identify the previous line searched and hence ensure that no large areas were missed or were searched twice. The distance searched on either side of the marker opposite the dump site depended on the time available for the search. During the night time searches the battery of the UV light limited the duration of the search to approximately 1 hour while during the day the searches could last for up to 2.5 hours. It was therefore possible to search a considerable portion of the beach during the day searches but a lesser portion at night.

For the night time searches the portable UV light was attached to the lower end of a pole so it could be used like a metal detector. The sensitivity of this method was tested by throwing some dyed pebbles on the beach and then searching for them with the UV light. All of the pebbles used in these tests were readily recovered showing that this method had high sensitivity, at least for pebbles.

During the early searches it was decided to concentrate on searching for pebbles because it was felt that finding any finer tracer would be almost impossible.

6.8 BEACH OBSERVATIONS

Daily observations were made at the beach at Washdyke approximately five times a week for the duration of the experiment. Observations included wave height and period, breaker angle, and littoral current speed and direction. The current speed and direction was determined by measuring the distance a float, usually a piece of wood from the beach, travelled during a set time. On many occasions local circulation around beach cusps markedly influenced the current measurement and therefore limited the value of these data.

6.9 RESULTS

Only three tracer pebbles were found on the foreshore of the beach, all on daytime searches. The first pebble was found 6 days after the release, 17 m to the south of the marker and approximately 12 m up the beach from the water line at low tide. The second pebble was found 11 days after the release, 110 m to the south of the marker and approximately 18 m up the beach from the water line at low tide. The third pebble was found 35 days after the release, 3 m to the north of the marker and approximately 17 m from the water line at low tide. All three pebbles were found on cusp horns and all had suffered some abrasion of the fluorescent dye. Subsequent tests, however, showed that all of the pebbles still glowed well under UV light. Table 6.4 gives the a- , b- , and c-axes for each of the tracer pebbles that were recovered.

TABLE 6.4 DIMENSIONS AND SHAPE PARAMETERS FOR RECOVERED TRACER PEBBLES, EXPERIMENT 3.

PEBBLE NUMBER	A-axis (mm)	B-axis (mm)	C-axis (mm)	b/a	c/b	Type	ψ
1	24.9	24.1	7.2	0.97	0.30	Disc	0.65
2	33.9	28.4	11.8	0.84	0.42	Disc	0.66
3	45.6	26.8	8.6	0.59	0.32	Blade	0.48

During the 35 day period within which pebbles were recovered only 20 wave and current observations were made at the beach. For this reason it was thought that wave data recorded by the wave recorder would provide a better indication of wave conditions during the experiment. Wave refraction diagrams could not be used to calculate shoaling coefficients because there was insufficient wave direction data. Therefore no attempt was made to correct the wave recorder data for shoaling effects.

Mean, maximum and minimum significant wave height and period are given in table 6.5 for the periods from the release to the finding of each pebble. Mean significant wave height was greatest for the first period, with $\bar{H}_s$ = 1.18 m, and slightly lower for the second two periods with $\bar{H}_s$ = 0.99 m and $\bar{H}_s$ = 1.02 m respectively. As would be expected the range of H_s increased from 1.86 m for the first period to 2.05 m for the third period. The range of T_s also increased, being 4 s for the first period and 10 s for the third period.

TABLE 6.5 WAVE STATISTICS FROM RELEASE UNTIL FINDING OF PEBBLES DURING EXPERIMENT 3.

RELEASE TO FINDING OF	$\overline{H}_s$ (m)	$\overline{T}_s$ (s)	MAX. H_s (m)	MIN. H_s (m)	MAX. T_s (s)	MIN. T_s (s)	MEAN STEEPNESS
Pebble 1	1.18	9	2.50	0.64	11	7	0.009
Pebble 2	0.99	10	2.50	0.47	12	6	0.007
Pebble 3	1.02	11	2.50	0.45	15	5	0.007

Table 6.5 includes a mean wave steepness value for each period, calculated from Ho/Lo, where Ho is the deepwater wave height and Lo is the deepwater wavelength. Ho was assumed to be equal to the recorded height, H_s, and Lo was calculated from the wave period T_s as follows:

$$Lo = 5.12\ T_s^2 \qquad 5.2$$

Figure 6.1 shows the current velocity measurements obtained throughout the period during which pebbles were found. The gaps in the zero line indicate days when observations were not made, which make up 33%, 36% and 43% of each period respectively. The observations in figure 6.1 show that a southward flowing current dominated.

Shape parameters for the recovered pebbles are shown in table 6.4. Two of the pebbles were discs and the other was a blade. The blade had a lower sphericity value, ψ, than either of the two discs.

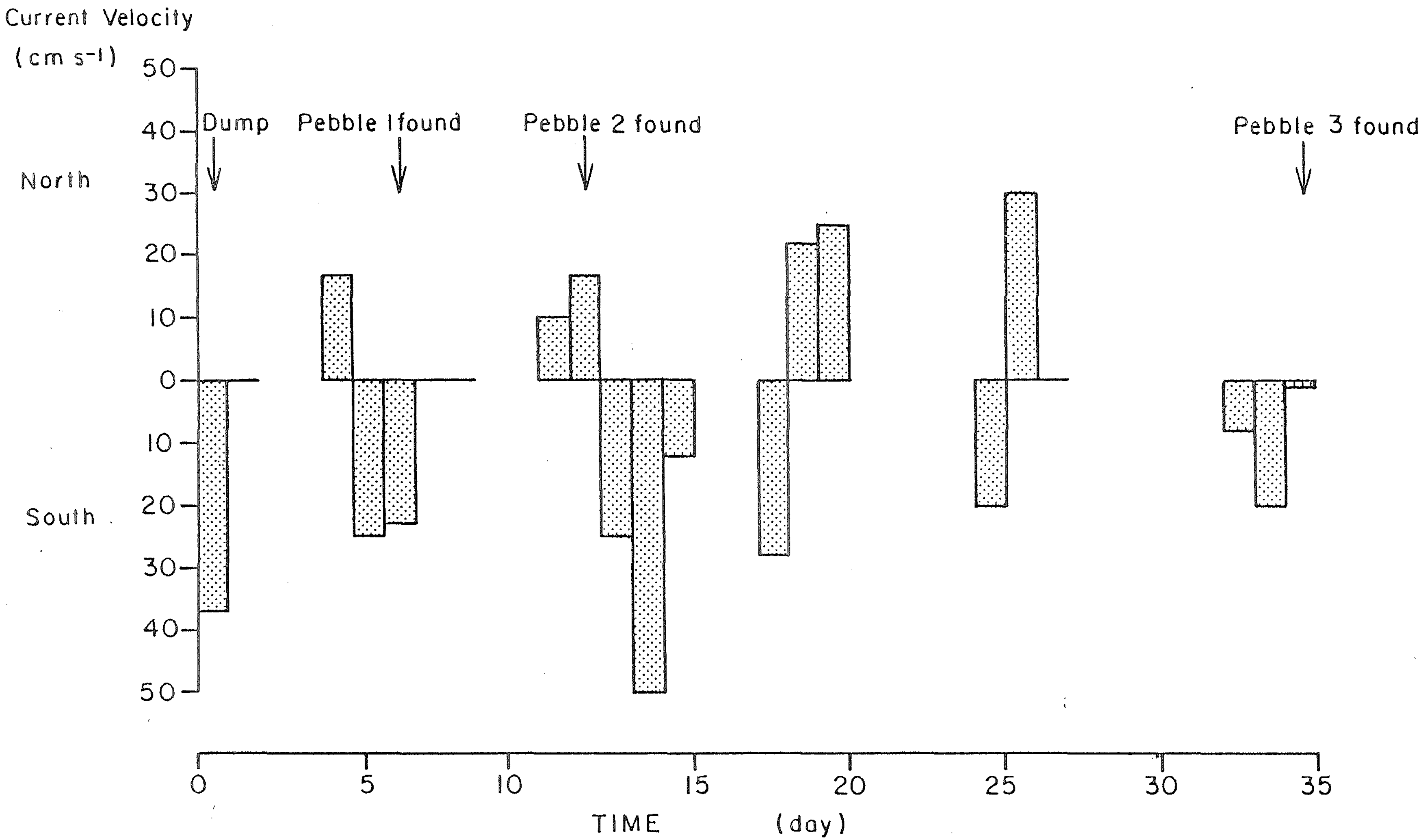


FIGURE 6.1 CURRENT VELOCITY AT WASHDYKE BEACH DURING THE PEBBLE RECOVERY PERIOD, EXPERIMENT 3. GAPS IN THE ZERO LINE INDICATE DAYS WHEN OBSERVATIONS WERE NOT MADE.

6.10 DISCUSSION

6.10.1 Offshore Supply Of Sediment

The finding of three pebbles on the foreshore of the beach has shown that it is possible for sediment to move from the continental shelf to a mixed sand and gravel beach. This finding, in conjuction with the finding of a landward movement of coarse sediments on the seafloor 1.4 km offshore during experiment 1, points to some offshore supply of sediment to the beach. The supply would appear to be small, partly because of the small amount of coarse material on the shelf and partly because of the slow rate of movement of this coarse material across the seafloor towards the beach. For example, the numerical average transport rate of granules for the final three sample runs in experiment 1 was 0.008 m^3 m^{-1} day^{-1}. Even if the offshore supply is small, its contribution could still be of importance to this severely undernourished beach which has had its main sediment supply, longshore transport, substantially reduced.

The finding of only three pebbles during this experiment means that the recovery rate was extremely low. Possible explanations for such a low recovery rate include the following:

a) Some of the tracer material did not move from the dump site to the beach.

b) Some of the tracer material may have become buried at the dump site.

c) Tracer material may have moved onto the near-shore face but not ascended to the foreshore of the beach.

d) Tracer material may have been buried on the foreshore and was therefore not found during the searches.

e) Dilution rates may have been too great for the sensitivity of the detection method used.

f) Tracer material may have moved out of the area being searched.

6.10.2 Wave Conditions

Mean wave height during the period of pebble recovery was slightly higher than the average for the full set of wave data given in table 3.3. It should be remembered that the wave recorder was located approximately 3 km offshore (see fig. 3.8) and therefore wave heights at the beach would be greater than those given due to the effects of shoaling. This would increase the average significant wave height to in excess of 1.0 m for the recovery period.

It is difficult to compare the wave statistics directly with the pebble recovery because it is not known exactly when the pebble reached the foreshore of the beach. For example, the pebbles that were found could have been on the foreshore for several days, possibly buried, before they were found. What can be said from the wave statistics is that waves with an average significant height slightly greater than 1.0 m, and an average significant period ranging from 9 - 11 s, are capable of moving pebbles up to 28.4 mm in median diameter from the seafloor to the foreshore of a mixed sand and gravel beach.

The on-offshore transport of sediment across a beach profile has often been associated with wave steepness. Laboratory experiments have produced a range of critical steepness values below which accretion occurs and above which erosion occurs. The critical values for accretion range from 0.025 (Johnson 1949) to 0.012 (King and Williams 1949). The mean wave steepness values given in table 6.5 were below these critical values and therefore the finding of some pebbles on the foreshore agrees with the results from these laboratory experiments.

6.10.3 Longshore Movement

Figure 6.1 shows that the current observations made at the beach during the pebble recovery period indicate a dominant current direction to the south, which is where the first two pebbles were recovered. However, because of the problem of local circulation around cusps affecting measurements, and because of the missing observations it is not possible to directly compare the longshore component of pebble movement with the current observations. If this was to be done a more complete set of current observations would have to be made and a better means of obtaining the current velocities and directions would be required.

The fact that the longshore component of movement for one of the recovered pebbles was 110 m in 11 days shows that a considerable amount of longshore movement can occur. The net longshore movement over a longer time period is, however, likely to be much less due to reversals in the direction of movement. For example, from 231 daily longshore current measurements Kirk (1981) found that 45% of the time the current flowed north, 43% of the time the current flowed south and 12% of the time there was no longshore current. The median current velocity was found to be 22 cm s^{-1} for both the north and south currents although the maximum recorded current flowing north was 27 cm s^{-1} greater than the maximum recorded current flowing south. The fact that the third recovered pebble had moved a relatively small net distance from the marker in a direction opposite to the first two pebbles supports the theory that current reversals reduce net movement.

It is not known whether the longshore movement of the recorded pebbles occurred on the seafloor, on the nearshore face, or on the foreshore of the beach, or whether there were any reversals in the direction of movement. The detailed pattern of movement is likely to be very complex.

6.10.4 Pebble Shape

Selective shape sorting across the profile as outlined in section 6.3 meant that any tracer pebbles found on the foreshore should have been relatively flat with low sphericity values. This was in fact the case for the three pebbles that were found, two of which were discs and the other a blade. Table 6.4 shows that the blade had the lowest sphericity value, ψ, and that the sphericity values for the two discs were approximately equal to the average sphericity value shown in table 6.2 for the nearshore face sample from South Beach.

Although it is difficult to be confident in the results from three pebbles, the experiment has certainly not provided any evidence which contradicts the theory of shape sorting outlined in section 6.3. Such a sorting process across the profile provides another possible explanation as to why recovery rates were so low for this experiment.

6.11 CONCLUSION

Despite the extremely low recovery rate this experiment did show that the continental shelf is a possible source of sediment for the mixed sand and gravel beach enclosing Washdyke Lagoon, and therefore for the other mixed sand and gravel beaches in the study area as well. The rate of supply was not measured but it is probably small, especially relative to other components in the sediment budget, particularly longshore transport.

Movement of pebbles from the seafloor to the beach occurred when wave conditions were only slightly greater than the average for the full set of wave data and therefore movement could be expected throughout much of the year. These findings are therefore different from the findings of Kidson and Carr (1959) who concluded from a tracer study that no transfer of sediment could take place between the offshore seabed and the shingle beach at Orfordness, Suffolk, except possibly under the most severe conditions.

No significant conclusions could be drawn with respect to the comparison of the longshore component of movement of the recovered pebbles with the longshore current observations because of the poor quality of the longshore current data. The average longshore component of movement for one pebble of 10 m day^{-1} suggested that considerable longshore movement can occur. However, over longer time periods reversals of current direction would mean that the net movement would be considerably smaller than this value. This theory is supported by longshore current observations from Kirk (1981) and by the finding of the third pebble a relatively small net distance from the marker and in a direction opposite to that of the first two pebbles.

The tracer pebbles that were found on the foreshore were all relatively flat, as would be expected if shape sorting across the profile had occurred. Because only three pebbles were found it is argued that this finding does not contradict the theory of shape sorting outlined in section 6.3 rather than that it provides clear evidence in support of the theory.

CHAPTER VII

AN ALTERNATIVE TRACER TYPE

7.1 INTRODUCTION

The various artificial tracers that have been in the marine environment were arbitrarily classified in section 1.4.7.2 into six types, based on their distinguishing property or characteristic. The types identified were:

a) Foreign Tracers
b) Magnetic Tracers
c) Coloured Tracers
d) Radioactive Tracers
e) Fluorescent Tracers
f) Chemical Tracers

The experiments reported in this study to date have involved the use of fluorescent tracer; and in one case, the use of a magnetic tracer. Fluorescent tracers were used because large quantities could be produced relatively easily with little cost, several sediment sizes could be traced simultaneously and detection, while a slow and laborious process, required only a dark room and a UV light. Fluorescent tracers, however, have several disadvantages which were outlined in section 1.4.7.2. Because of these disadvantages it was desirable to find an alternative tracer type that could be used to trace fine nearshore sediment in New Zealand. It was also desirable to use this alternative tracer type simultaneously with fluorescent tracer in a field experiment so that the results from the two tracer types could be compared.

Foreign tracers were rejected, firstly because of the difficulty of finding a substance that would behave hydrodynamically the same as the native sediment and, secondly, because of the difficulty of detection. A magnetic tracer had been tried in experiment 1 and was found to be unsatisfactory and so this type of tracer was also rejected. Coloured tracers suffer from all of the disadvantages of fluorescent tracer and in addition detection is difficult. They were therefore also rejected as a possible alternative tracer type. This left either radioactive or chemical tracers.

The possibility of undertaking a radioactive tracing experiment was discussed with scientists from the Australian Atomic Energy Commission, the Department of Scientific and Industrial Research, Institute of Nuclear Sciences, Lower Hutt, and the Department of Health, National Radiation Laboratory, Christchurch. The problems associated with such an experiment included the purchase of radioactive material from overseas (there is no nuclear reactor in New Zealand capable of producing the required radioactive isotopes), the cost of such material, the availability of the specialised detection equipment required and various safety aspects. It was concluded from the initial investigation that it would be possible to undertake a radioactive tracing experiment but that it was not feasible for a study of this kind.

Having eliminated the possibility of using radioactive tracer the only alternative remaining was to use a chemical tracer. During the initial investigations to find a suitable chemical tracer and the subsequent analysis of tracer samples, considerable assistance was received from the Department of Scientific and Industrial Research, Institute of Nuclear Sciences, Lower Hutt, and the Departments' of Chemistry and Geology, University of Canterbury.

7.2 CHEMICAL TRACERS

When using chemical tracers to study sediment transport sediment is labelled with an element that is not present naturally, or which is present in very low concentrations. The labelled sediment is then released and samples collected in the same manner as for a fluorescent tracing experiment. The samples are returned to a laboratory where a chemical detection technique is used to determine the concentration of tracer present in each sample. This information can be used to draw dispersion patterns and to calculate sediment transport rates in the same manner as for a fluorescent tracing experiment.

Chemical tracers have been used successfully in field experiments by Malone (1969) and Leahy et al. (1976) (see also Ecker, Sustar and Harvey 1977). Malone labelled sand with europium (Eu) and subsequently used neutron activation analysis for detection. Leahy et al. used iridium (Ir) for labelling and also used neutron activation for detection. For the present study the labelling procedure used by Malone was chosen for further investigation. The use of iridium was ruled out because of the excessive cost of this element.

7.3 LABELLING PROCEDURE

The general procedure used by Malone (1969, p. 12) for labelling sand was to remove shell from the sand by acid digestion, dry the sand and then wet it with a solution of a rare-earth nitrate. The sand was again dried to deposit the salt on the sand grains and then baked at 750 - 800° to convert the nitrate to an insoluble oxide which adheres strongly to the sand.

Initial tests were carried out using cadmium (Cd) to label sand using the method described above. Cadmium was chosen because it is the most sensitive element for detection with atomic absorption spectroscopy. Although the tests were successful the idea of using cadmium was abandoned because of its extreme toxicity.

At this point it was decided to use europium as the tracer element.

7.3.1 Labelling Sand With Europium

Initially 200 g of sand from Caroline Bay was labelled with Eu to enable the detection method to be tested. The labelling method used differed in two ways from that outlined by Malone (1969, p. 17). Firstly, the quantity of sand labelled was much less and, secondly, $EuCl_3$ (europium trichloride) was used instead of Eu_2O_3 (europium sesquioxide).

A europium solution was made by dissolving 0.4994 g $EuCl_3$ in approximately 1 ml concentrated HNO_3 (nitric acid) and diluting this to 100 ml. The 200 g of sand to be labelled was soaked overnight in a 1 M solution of HCl (1 part water: 11 parts concentrated hydrochloric acid) to remove shell. The sand was then thoroughly washed with tap and then distilled water before being dried. The dried sand was weighed out in 50 g lots which were placed in small porcelain dishes. Each lot of sand was then wet with 13 ml of the europium solution, oven dried at 100°C and baked in a kiln at 800°C for 30 minutes.

Having produced labelled sand a suitable detection technique had to be found.

7.4 DETECTION TECHNIQUES

Nelson and Coakley (1974) list four possible chemical detection techniques that can be used. They are neutron activation analysis, X-ray fluorescence, atomic emission analysis and atomic absorption analysis. Each of these four methods was investigated and assessed as a possible option for the present study.

7.4.1 Neutron Activation Analysis

For neutron activation analysis a sample is irradiated in a nuclear reactor for a specified time. When irradiated most elements form radioactive isotopes which, provided their decay involves gamma-ray emission, can be identified quantitatively through the use of gamma-ray detectors since the energies of the gamma-rays are characteristic of the isotope (Nelson and Coakley 1974).

If this technique was to be used samples would have to be sent overseas for irradiation although it was possible that detection could be undertaken at the National Radiation Laboratory, Christchurch. The Australian Atomic Energy Commission, which has a suitable reactor at Lucas Heights, New South Wales, was contacted but was unable to provide the service at the levels that would have been required. Neutron activation analysis was therefore unavailable as a detection technique for this study.

7.4.2 X-ray Fluorescence

When using X-ray fluorescence a sample is irradiated with a broad spectrum of primary X-rays from an

X-ray tube. This results in the emission of secondary, fluorescent X-rays from the elements present in the sample. By identifying and measuring the intensity of these secondary X-rays the concentrations of particular elements in the sample can be determined (Wells and Childs 1978).

The Department of Geology, University of Canterbury, have a suitable X-ray fluorescence spectrometer and enquiries were made regarding its possible use for the present study. These enquiries revealed that the instrument was in considerable demand but that it could be used for the present study if required. If X-ray fluorescence was used sample preparation would involve crushing the sand and then using this crushed material to form small disks or pellets which could be placed in the machine for analysis. Standard samples containing known quantities of Eu would also have to be prepared to provide a calibration curve for the instrument.

7.4.3 Atomic Emission Analysis

For analysis using atomic emission (flame emission) a sample, which must be in solution form, is aspirated into a flame. This results in the elements present being atomised into excited atomic states which then emit characteristic electromagnetic radiation (light rays). The radiation is passed into a selective filter, a prism, or a diffraction grating which selects a specified narrow portion of the spectrum and directs this to a suitable light intensity detector. This detector transforms the signal into electrical energy which is then recorded (Buell 1972). These measurements can then be compared with results from standard samples to determine the concentration of the element present.

A suitable atomic absorption spectrophotometer which could be operated in an emission mode is available in the Department of Chemistry, University of Canterbury. Samples for analysis would either have to be digested or subjected to leaching to obtain a solution suitable for analysis. Standard samples would also have to be prepared to provide a calibration curve for the instrument.

7.4.4 Atomic Absorption Analysis

Atomic absorption analysis is carried out using an instrument very similar to that used for atomic emission analysis. The difference is that a light beam from a source of monochromatic radiation, with a wavelength characteristic of the element being detected, is directed so that it passes through the flame. When a sample is aspirated into the flame atoms are formed which absorb light at characteristic wavelengths (Buell 1972). Therefore, the greater the concentration of the element being detected the higher the absorption of the beam of monochromatic light. Standard solutions are used to provide a calibration curve of absorbance *versus* concentration.

A suitable atomic absorption spectrophotometer is available in the Department of Chemistry, University of Canterbury. However, the Department did not possess the required Eu lamp to provide the monochromatic radiation for

Eu detection. Therefore, if this technique was to be used an Eu lamp would have to be purchased. Sample preparation would be the same as for atomic emission analysis.

7.4.5 Choice Of Detection Technique

X-ray fluorescence, atomic emission analysis and atomic absorption analysis were all possible detection techniques for Eu. It was not possible to try them all so one had to be chosen for further investigation. One factor of prime importance in the selection was the lower limit of detection of Eu, which provides a measure of the sensitivity of the technique. For Eu detection atomic emission provides greater sensitivity than atomic absorption and for concentration below 10 $\mu g\ ml^{-1}$ (ppm) it is the preferred technique of the two (Anon 1979). Therefore the choice was between X-ray fluorescence and atomic emission. The latter was chosen because Reeves and Brooks (1978, p. 222) quote the detection limit for Eu as 0.0006 $\mu g\ ml^{-1}$ (ppm) and because the instrument required was more readily available. It was thought that the sample preparation would take approximately the same time for both techniques.

7.5 LABORATORY TESTS

Having decided to use atomic emission analysis as the detection technique it was necessary to carry out laboratory tests to decide on the best method of sample preparation and to establish the capabilities of the instrumental method of analysis. Also, it was important to establish the background level of Eu in sands from the study area.

7.5.1 Sample Preparation

Two different methods were used for removing Eu from sand grains in a solution form suitable for analysis. The first method involved complete dissolution of the sand grains and the second method involved acid leaching.

a) Dissolution Method

1. A sample was repeatedly split using a micro-sample splitter until a subsample of approximately 0.5 g remained.

2. The subsample was crushed by hand in a mortar and pestle.

3. An amount of crushed sand was weighed out and placed in a platinum crucible. The exact amount depended on the expected concentration of Eu in the sample and ranged from 0.1 g for labelled sand to 0.25 g for unlabelled sand.

4. The crucible was heated to red heat over a burner to remove organic material from the sample of crushed sand.

5. The sample was moistened with 2 - 3 drops of distilled water.

6. 6 mls of HF (hydrofluoric acid) and 0.6 ml $HClO_4$ (perchloric acid) were added.

7. The crucible was heated on a sand bath at 230° C until fuming stopped. The sand bath was placed on a hot plate in a fume cupboard.

8. A further 0.6 ml of $HClO_4$ was added and the sample reheated until the fuming again stopped.

9. The crucible was removed from the sand bath and the residue taken up in 4 ml 6 M HCl (1 part water: 1 part concentrated HCl).

10. The contents of the crucible were poured into a 25 ml flask which was topped up with distilled water.

b) <u>Leaching Method</u>

1. A sample was repeatedly split using a micro-sample splitter until approximately 0.5 g remained.

2. An amount of crushed sand was weighed out and placed in a 100 ml beaker. The exact amount depended on the expected concentration of Eu in the sample and ranged from 0.3 g for labelled sand to 0.5 g for unlabelled sand. During later analysis much larger samples were used.

3. 20 ml 4 M HNO_3 (3 parts water: 1 part concentrated HNO_3) was added to each beaker.

4. The beaker was covered with a glass lid, placed on a hot plate in a fume cupboard and boiled for 30 minutes.

5. The remaining solution was filtered through a "Whatman Grade 50" filter paper into a 50 ml flask. The beaker and filter paper were repeatedly flushed with distilled water to ensure all of the Eu solution was

transferred to the 50 ml flask. Once the filtering was finished the flask was topped up with distilled water.

The solutions obtained by these two methods were stock solutions. Subsamples of 2.5 ml or 5 ml taken from the stock solution were diluted and analysed by atomic emission.

7.5.2 Standard Preparation

In order to obtain quantitative measurements of Eu concentrations by atomic emission analysis standard solutions containing known concentrations of Eu were prepared. These standards can either be analysed separately or added to the sample using the standard addition technique.

Exactly 0.0170 g $EuCl_3$ was weighed out, dissolved in 5 ml of 6 M HCl and diluted to 100 ml. This gave a solution of exactly 100 ppm Eu.

When separate standards were used samples of 100 ppm Eu solution were diluted to give standard solutions ranging from 1-8 ppm Eu. These solutions were analysed and the results plotted to give a calibration curve of relative emission *versus* concentration. When the standard addition technique was used aliquots of the solution to be analysed were placed in four standard flasks. Known different amounts of 100 ppm solution were added to all but one of the flasks which were then topped up with distilled water. After the solutions had been analysed the unknown concentration, c, was determined graphically by plotting the relative emission as a function of the added standard concentration and extrapolating to zero emission at concentration -c. This is illustrated in figure 7.1.

7.5.3 Instrument

All samples were analysed using a "Varian Techtron AA- 1475 Series Atomic Absorption Spectrophotometer" used in the emission mode. The wavelength was set to 459.4 nm and the slit width to 0.2 nm, the lowest setting available. The flame was nitrous oxide-acetylene. When potassium had been added to the samples being analysed (see later) the instrument was zeroed on a distilled water solution containing the same concentration of potassium as the samples. Output was either in digital form using a running mean or from a chart recorder. Either could be used provided the standards were analysed in the same way. The measured concentrations were in $\mu g\ ml^{-1}$ (ppm) and these were converted to $\mu g\ g^{-1}$ of Eu in the original sand sample by using the following formula.

$$C=(c\ v_3\ v_1/v_2)\ /\ w \qquad 7.1$$

where C = concentration of Eu in the sand sample ($\mu g\ g^{-1}$)

c = concentration of Eu in the diluted stock solution ($\mu g\ ml^{-1}$)

v_1 = volume of the stock solution (ml)

v_2 = volume of the subsample taken from the stock solution (ml)

v_3 = volume of the diluted stock solution (ml)

w = weight of sand sample used in sample preparation (g)

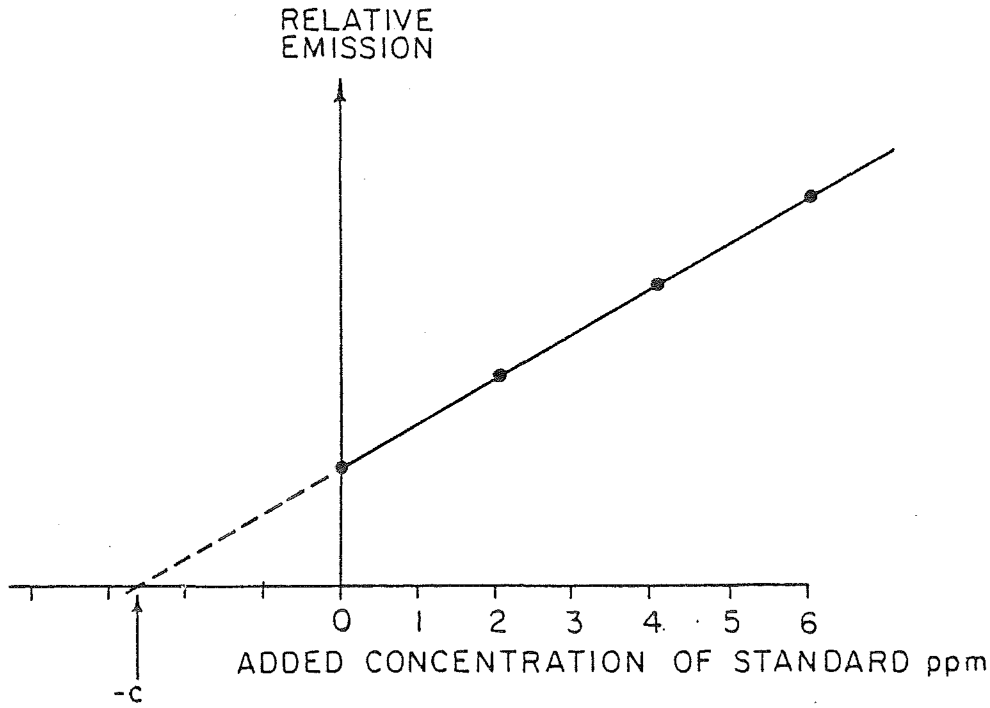


FIGURE 7.1 GRAPHICAL DETERMINATION OF THE UNKNOWN CONCENTRATION, c, WHEN USING THE STANDARD ADDITION TECHNIQUE.

7.5.4 Measurement Of Europium Concentrations

Two samples of Eu labelled sand and two samples of unlabelled sand from the study area were prepared using the dissolution method. These samples were analysed using separate standards. The samples of labelled sand were found to have Eu concentrations of 312 $\mu g\ g^{-1}$ and 297 $\mu g\ g^{-1}$ respectively, giving an average concentration of 305 $\mu g\ g^{-1}$. The unlabelled sand samples had Eu concentrations of 107 $\mu g\ g^{-1}$ and 102 $\mu g\ g^{-1}$ respectively, giving an average concentration of 105 $\mu g\ g^{-1}$. The difference in the average concentration of labelled and unlabelled sand was 200 $\mu g\ g^{-1}$, which indicated that the labelling process had raised the concentration of Eu by that amount. The calibration curve was linear but did not pass through the origin as would be expected. The background Eu level of 105 $\mu g\ g^{-1}$ was much higher than had been expected. Haskin and Gehl (1962), for example, found levels of Eu ranging from 0.088 ppm to 1.1 ppm in a variety of rock types. It was therefore decided to re-analyse one sample of labelled sand and one sample of unlabelled sand using the standard addition technique. The results showed an Eu concentration of 516 $\mu g\ g^{-1}$ in the labelled sand and 138 $\mu g\ g^{-1}$ in the unlabelled sand, which indicated that the labelling process had raised the concentration of Eu by 378 $\mu g\ g^{-1}$. The background level, however, was still higher than expected.

Atomic emission analysis is subject to several kinds of interference (Reeves and Brooks 1978, p. 221) and it was possible that this was the cause of the high background levels obtained. One type of interference is caused by the ionisation of an element in the flame. Eu is partially ionised by the nitrous oxide-acetylene flame. This ionisation can be suppressed by the addition of potassium chloride (KCl) solution to give a final concentration of 4000 μg ml^{-1} potassium in all solutions (Anon 1979). Another type of interference results from the formation of a stable compound in the solution. This type of interference can be eliminated by adding a releasing agent to all solutions (Reeves and Brooks 1978, p. 180). Tests were carried out to see whether the addition of potassium or a releasing agent would improve the detection of Eu.

One sample of labelled sand and one sample of unlabelled sand were prepared by the dissolution method. Two sets of diluted stock solutions were prepared for analysis by the standard addition technique. A 16 000 μg ml^{-1} potassium solution was made by dissolving 3.06 g KCl in water and diluting to 100 ml. The volume of the diluted stock solution (v_3) was 10 ml so 2.5 ml of the potassium solution was added to all solutions so that they had a final concentration of 4000 μg ml potassium. Lanthanum (La) was tried as a releasing agent. A 1% La solution was made by dissolving 1 g $La(NO_3)_3.6H_2O$ (lanthanum nitrate) in water and diluting to 100 ml. Exactly 1.5 ml of this solution was added to one set of the diluted stock solutions. The diluted solutions were analysed and Eu concentrations calculated.

The results are shown in table 7.1. The addition of potassium solution improved the Eu detection by increasing the measured concentration in the labelled sand and reducing the background level to zero. The addition of lanthanum solution as well as potassium solution reduced the measured concentration of Eu in the labelled sand. It was therefore decided that all solutions to be analysed should have a final concentration of 4000 μg ml^{-1} potassium but that lanthanum should not be added.

TABLE 7.1 MEASURED CONCENTRATIONS OF Eu IN SAMPLES OF LABELLED AND UNLABELLED SAND ANALYSED WITH THE ADDITION OF POTASSIUM (K) AND LANTHANUM (La) SOLUTIONS.

	LABELLED SAND		UNLABELLED SAND	
	K ADDED	K AND La ADDED	K ADDED	K AND La ADDED
CONCENTRATION (μg g^{-1})	682	443	0	0

Further tests were carried out to test the repeatability of measurements and to test various dilutions of labelled sand. Quantities of labelled sand were weighed out and mixed giving exactly 33.408%, 50.005% and 66.590% dilutions of labelled sand respectively. A sample from each dilution and two samples of labelled sand were prepared for analysis using the leaching method. Solutions were analysed on two different days using the standard addition technique. The results are shown in table 7.2. The difference between the measurements made on the two days varied from 0% to 7%. The measured dilution concentrations differed from the calculated values based on the average of the two labelled samples by up to 10%. From these tests it would appear that measurement errors of up to 10% can be expected.

TABLE 7.2 RESULTS OF REPEATABILITY AND DILUTION TESTS FOR EUROPIUM LABELLED SAND.

	Eu CONCENTRATION ($\mu g\ g^{-1}$)		
	DAY 1	DAY 2	PERCENTAGE DIFFERENCE
Labelled Sand 1	789	754	4
Labelled Sand 2	754	770	2
Average Labelled Sand	772	762	
33.408% Of Average	258	255	
33.408% Dilution	279	259	7
Percentage Difference	8	2	
50.005% Of Average	386	381	
50.005% Dilution	364	364	0
Percentage Difference	6	5	
66.509% Of Average	514	507	
66.509% Dilution	492	459	7
Percentage Difference	4	10	

7.5.5 Background Level Of Europium

Three samples of unlabelled sand from the study area and one sample of labelled sand were sent to the Department of Scientific and Industrial Research, Institute of Nuclear Sciences, Lower Hutt, for analysis of Eu content.

A method for the purification of acid leachable Eu (Eu^{2+}ion) was developed. This method and the resulting measurements, made by atomic emission analysis, are detailed in Ditchburn and McCabe (1982). The purification procedure increased the sensitivity of the measurement technique. Background levels of Eu found in the unlabelled sand samples were around 0.3 ppm and the average level of Eu found in the labelled sand was 650 ppm. The reason why the results presented in table 7.1 show the background level of Eu to be zero is simply because the detection technique used was less sensitive.

7.5.6 Discussion

Two methods of sample preparation were used to produce samples in solution form suitable for analysis by atomic emission. Both methods produced equivalent yields of Eu. The dissolution method was more time consuming than the acid leaching method and required considerable care when working with the hydrofluoric and perchloric acids. The acid leaching method is therefore considered to be the better of the two.

Two methods were also used to provide standards for quantitative analysis. When the standard addition technique is used any interference present will act on both the standard and sample solutions. The method is more time consuming than using separate standards and is only used to check the results from analyses using separate standards. If the results from the separate standards are acceptable then separate standards can be used for the remaining analyses. Because the only test using both methods was undertaken before it was decided to add potassium solution to all samples further checks using the standard addition technique were required.

All solutions to be analysed should have a concentration of 4000 μg ml^{-1} potassium to suppress ionisation of Eu in the flame. The measurement errors were found to be about 10% which would be acceptable for a sediment tracer experiment. Ditchburn and McCabe (1982) increased the sensitivity of measurement by using a purification procedure during the analysis. They found the background level of Eu to be about 0.3 ppm. This compares favourably with the Eu levels found by Haskin and Gehl (1962) for a variety of rock types.

The tests have showed that Eu labelled sand could be used in a sediment tracing experiment using atomic emission analysis for detection. The background level of Eu would, however, limit detection once dilutions of 10^4 had occurred.

7.6 FIELD EXPERIMENT

A small scale field experiment, experiment 4, using both fluorescent dyed sand and Eu labelled sand was planned and executed.

7.6.1 Aims

The experiment had the following aims:

a) To determine both the rates and directions of sediment transport from both fluorescent and Eu tracers.

b) To compare the rates and directions of sediment transport determined from the fluorescent and Eu tracers.

c) To look for relationships between the measured sediment transport rates and wave or wave-dependent parameters.

d) To assess the use of Eu labelled sand as a sediment tracer using atomic emission analysis for detection.

7.6.2 Location Of The Experiment

Because only small quantities of tracer were to be used for this experiment a site in Caroline Bay was chosen where the sediment transport rates were expected to be relatively low. It was decided to choose a site in Caroline Bay close to the North Mole in the hope that this would prevent boats from interfering with the grid. The site chosen was relatively close to shore because of the marked seaward fining of sediment close to the North Mole (see fig. 3.6). The location of the site is shown in figure 3.8. Water depth at the site varied between 1.5 m at low tide to 3.0 m at high tide.

7.6.3 Production Of Tracer

The amount of tracer that could be produced for this experiment was restricted by the high cost of Eu and it was decided to limit production to 15 kg of fluorescent tracer and 15 kg of Eu tracer. Sand for labelling was obtained from the foreshore of the beach in Caroline Bay and taken to the Physical Laboratory, Department of Geography, University of Canterbury. The fluorescent tracer was produced using the method outlined in section 4.3.2. Because insufficient $EuCl_3$ was available for the Eu tracer 20 g of Eu_2O_3 was obtained from overseas at a cost of $165. The Eu tracer was then produced using the exact method of Malone (1969, p. 17).

A sample of each tracer type and a sample of seafloor sand from the experiment site were subjected to grain size analysis by sieving. The resulting grain size curves are shown in figure 7.2 and the grain size characteristics of Folk (1974) (see appendix 1) are given in table 7.3. The fluorescent tracer had a mean grain size 0.16ϕ coarser than the sand from the experiment site. The Eu tracer had a mean grain size only 0.05ϕ coarser than the sand from the experiment site. The differences between the fluorescent tracer and the Eu tracer can be attributed to the formation of some aggregates during the fluorescent dyeing process and to the removal of shell from the Eu tracer. These effects would result in the size distribution of the fluorescent tracer having the coarse tail accentuated and the Eu tracer having the coarse tail reduced. These affects are clearly seen in figure 7.2 and result in the fluorescent tracer having a relatively coarser mean grain size.

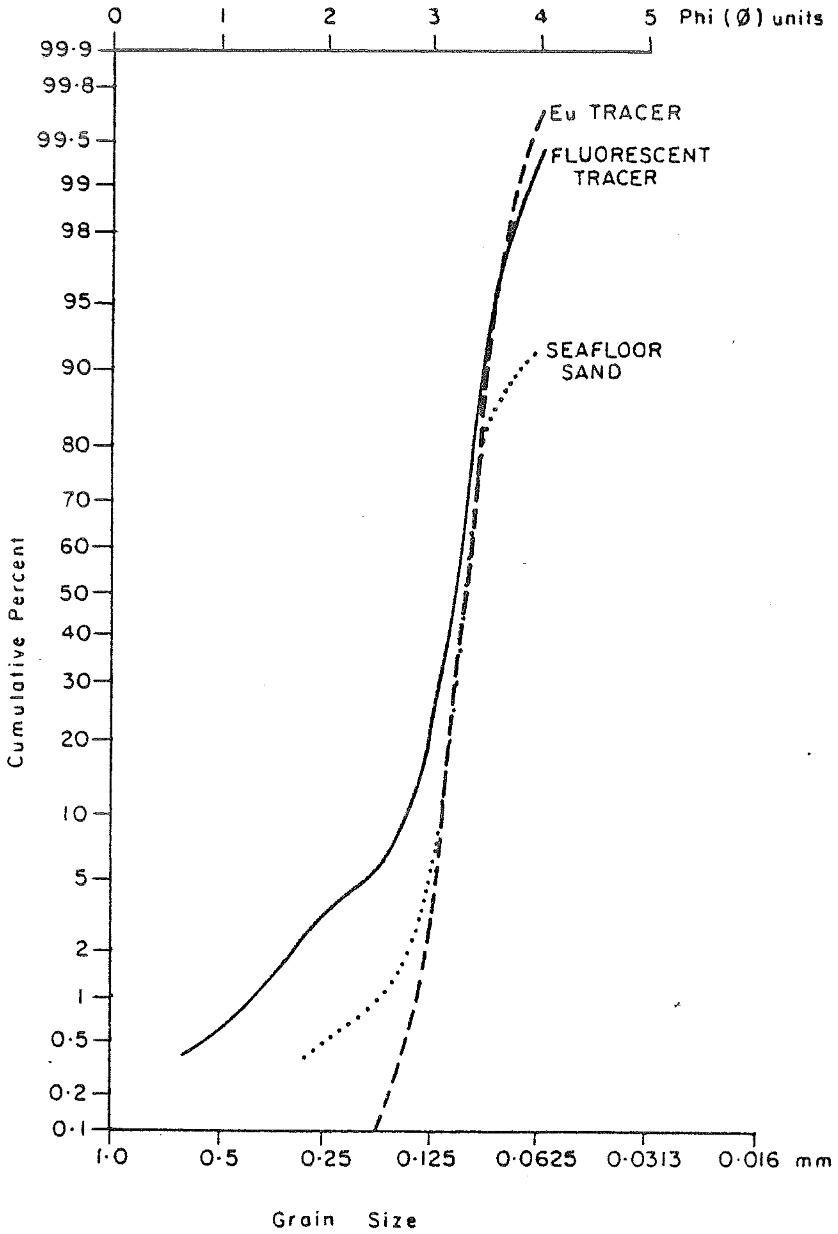


FIGURE 7.2 GRAIN SIZE CURVES FOR SAMPLES OF EUROPIUM (Eu) TRACER, FLUORESCENT TRACER, AND SEAFLOOR SAND FROM THE SITE OF EXPERIMENT 4.

TABLE 7.3 GRAIN SIZE CHARACTERISTICS FROM FOLK (1974) (SEE APPENDIX 1) FOR SAMPLES OF EUROPIUM (Eu) TRACER, FLUORESCENT TRACER, AND SEAFLOOR SAND FROM THE EXPERIMENT SITE.

SAMPLE	MEAN GRAIN SIZE			SORTING		SKEWNESS	
	ϕ	mm	Class	Value	Verbal	Value	Verbal
Seafloor Sand	3.33	0.0994	very fine sand	0.34	very well sorted	0.28	fine skewed
Fluorescent Tracer	3.17	0.1111	very fine sand	0.31	very well sorted	-0.32	coarse skewed
Eu Tracer	3.28	0.1029	very fine sand	0.18	very well sorted	-0.02	near symmet-rical

7.6.4 Sampling Grid

As in experiments 1 and 3 the rates and directions of tracer movement in this experiment were to be determined by the spatial integration technique. A sampling grid was therefore required. A 6 x 8 m rectangular grid containing 20 sampling points was constructed using steel reinforcing rods linked together with a thin cord. An outline of the grid and its orientation are given in figure 7.3. Each corner of the grid was marked with a labelled buoy.

Prior to laying the grid the cord lines were cut to the appropriate lengths and loops were inserted for the rods. The author and another diver working from a small boat laid the grid in the following way. First, the rod at

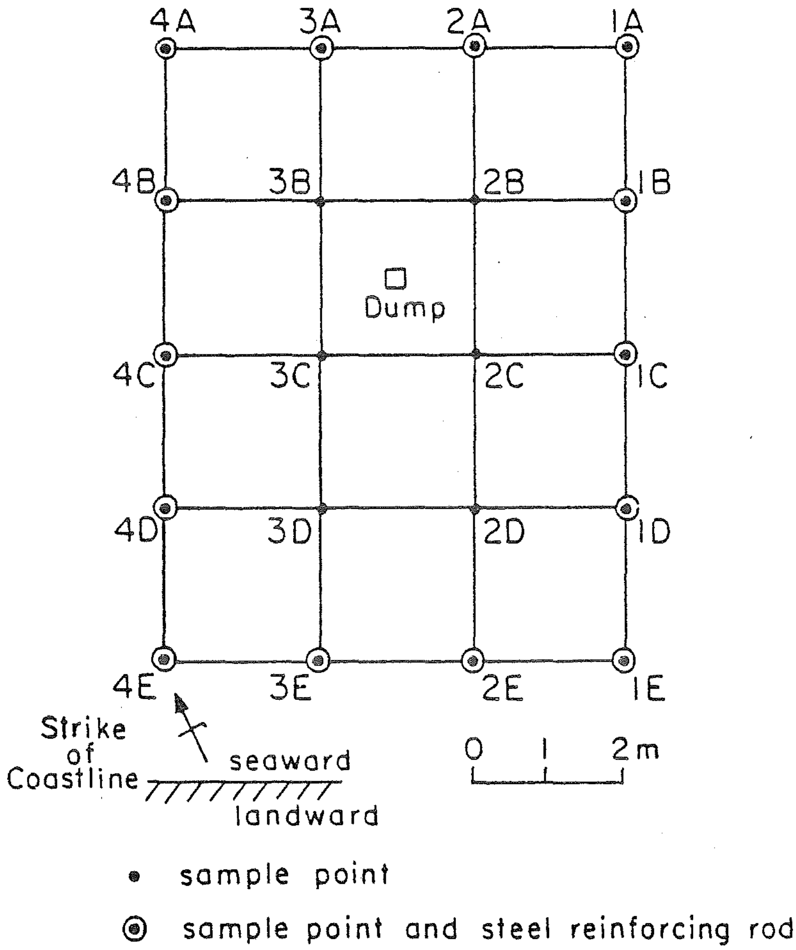


FIGURE 7.3 SAMPLING GRID FOR EXPERIMENT 4.

1A was driven in and the appropriate buoy attached. Line 1 was then run out parallel to the North Mole and its orientation checked with an underwater compass. A rod was then driven in at 1E and the appropriate buoy attached. A 10 m line was attached to the rod at 1E and line A was attached to the rod at 1A. The intersection of the end points of these two lines gave the position of 4A. A rod was driven in at 4A and line A and the appropriate buoy attached. The 10 m line was then removed. Line 4 was attached to the rod at 4A and line E attached to the rod at 1E. The intersection of the end points of these two lines gave the position of 4E. A rod was driven in at 4E and lines 4 and E were attached. The final buoy was also attached to the rod at 4E. Rods were driven in at the marked positions along each line and lines 2, 3, B, C and D were then run between the appropriate rods. Finally, identification labels were attached to each sample point. Where the sample point consisted of the intersection of two lines, for example 2B, the short lengths of cord used to tie on the identification labels were also used to tie the two lines together.

The dump site was located by tying temporary lines from 2B to 3C and from 2C to 3B. These lines were removed after the tracer was released.

7.6.5 Release Of Tracer

Because of the small quantity of tracer being used for this experiment and the small grid size it was essential to ensure that all of the tracer was released exactly at the dump site. The best way of ensuring that this was the case was to use a diver to release the tracer. The fluorescent and Eu tracers were thoroughly mixed and placed in two tins. The tracer in each tin was pre-wet with a mixture of water and detergent. The tins were then loaded aboard a small boat and taken to the grid where the author carried each tin to the bottom and released the tracer. A considerable amount of tracer appeared to be temporarily suspended during the release. No mound was apparent on the bottom following the release.

7.6.6 Sample Collection

Volumetric samples were collected from the sampling grid on six occasions following the tracer release. The first samples were collected after 0.15 days and the final samples after 3.92 days. Sample collection was ended as planned at that point despite the fact that a considerable amount of tracer was still visible at the dump site. The sampling period was not extended because it was not possible to continuously watch the grid during the following two days to warn any swimmers in the area to keep well away. The grid, with its rods and lines, was potentially dangerous for swimmers, especially at low tide.

The sample tubes that had been used for experiment 2 were again used for this experiment, although the rubber discs on the pistons were renewed. Some additional pistons and tubes were made so that two complete sets of sample tubes were available. This meant that two sample runs could be made before it was necessary to inspect the cores and transfer them to plastic bags.

The samples were collected by the author and another diver working from a small boat. The divers were assisted by two surface attendants. Core tubes were taken to the bottom in a netting bag and driven in with the aid of a hammer. The two divers each sampled half of the grid and all samples were easily obtained within 15 minutes. When taking a sample the divers had to avoid choosing the exact spot used for a previous sample because holes left where previous samples had been taken were not infilled.

Once back on shore all samples were plunged from their core tubes, broken in half longitudinally with the aid of a spatula, taken into a dark room and inspected with a UV light. The maximum depth of tracer mixing was recorded and that section of the core containing tracer was then placed in a labelled plastic bag. The remaining section of the core was discarded. The samples were then taken to the Physical Laboratory, Department of Geography, University of Canterbury, for further analysis.

7.6.7 Wave Data

This experiment was carried out following the completion of the wave height and period data collection using the wave recorder. It was therefore decided to place the wave recorder in Caroline Bay for the duration of the experiment. The sensitivity of the recorder was changed from low to high because of the much smaller waves that were expected in Caroline Bay. The recorder was deployed at the position shown in figure 3.8 prior to the tracer release and recovered after the final sample run. In addition, some visual observations were made of wave height, period, and direction throughout the experiment.

7.6.8 Analysis

All samples were analysed firstly for fluorescent tracer and then some were chosen for Eu tracer analysis. The analysis procedure outlined in section 5.6 was used to determine the concentration of fluorescent tracer in each sample. On five occasions steps 4-8 were repeated to test the accuracy of the splitting and counting technique. The results of these tests are shown in table 7.4. The average difference in the calculated tracer concentration was 9% and the largest difference occurred in the sample with the lowest concentration.

TABLE 7.4 RESULTS FROM TESTS CARRIED OUT TO TEST THE ACCURACY OF THE SAMPLE SPLITTING AND COUNTING TECHNIQUE USED IN THE ANALYSIS OF FLUORESCENT TRACER FROM EXPERIMENT 4.

		TEST NUMBER				
		1	2	3	4	5
luminophors g^{-1}	1	268	1090	84	366	26
luminophors g^{-1}	2	248	1040	90	352	33
% difference		7	5	7	4	21

The total number of luminophors present in each sample was calculated from equation 5.1, although the summation was not required because there was only one core section for each sample. The results were fed into the University of Canterbury's "Prime 750" computer where they were converted to logarithms. A contouring routine was then used to plot a dispersion pattern for the fluorescent tracer for each sample run. The x and y co-ordinates of the centroid of each dispersion pattern were calculated from equations 4.1 and 4.2 with the tracer concentration at each sample point being replaced by the total number of luminophors in each sample. As with experiments 1 and 2 an average grain velocity V (magnitude and direction) was calculated for each sample run from the positional shifts of the centroid between successive sample runs.

The recorded depths of tracer mixing were plotted on an outline of the grid for each sample run to reveal the spatial pattern of mixing. The thickness of the mobile layer E was estimated for each sample run by averaging the recorded mixing depths.

The sediment transport rate q was calculated for each sample run using equation 4.4.

Sample 2B from sample run 6 contained the highest concentration of luminophors. It was therefore decided to analyse this sample and the samples with the next two highest concentrations from this sample run (2C and 3C) for Eu tracer. Samples were prepared for analysis using the acid leaching method and the standard addition technique was used. Because the concentration of

Eu was expected to be low samples of 4.0 g were used. After the results from these samples were known it was decided to re-analyse the samples, along with all other samples from sample run 6, for Eu tracer. In addition a sample of unlabelled sand from the experiment site and a sample of labelled Eu tracer sand were analysed. The acid leaching method was again used and it was decided that separate standards could be used. During the measurements the standard solutions were read every five samples and a separate calibration curve was plotted for each reading.

7.6.9 Results

7.6.9.1 Fluorescent Tracer

The dispersion pattern for each sample run is shown in figure 7.4. Included on each pattern is the calculated centroid position. The movement of the centroid over time is shown in figure 7.5. The maximum displacement of the centroid from the dump site was 1.2 m for sample run 3.

The recorded maximum depths of tracer mixing in each sample for each sample run are shown in figure 7.6. The maximum recorded depth of tracer mixing was 0.04 m for sample 4C from sample run 6.

The time between each sample run, centroid displacement, average grain velocity V, estimated thickness of the mobile layer E and sediment transport rate q for each sample run are given in table 7.5. The maximum sediment transport rate was 0.020 m^3 m^{-1} day^{-1} for sample runs 1

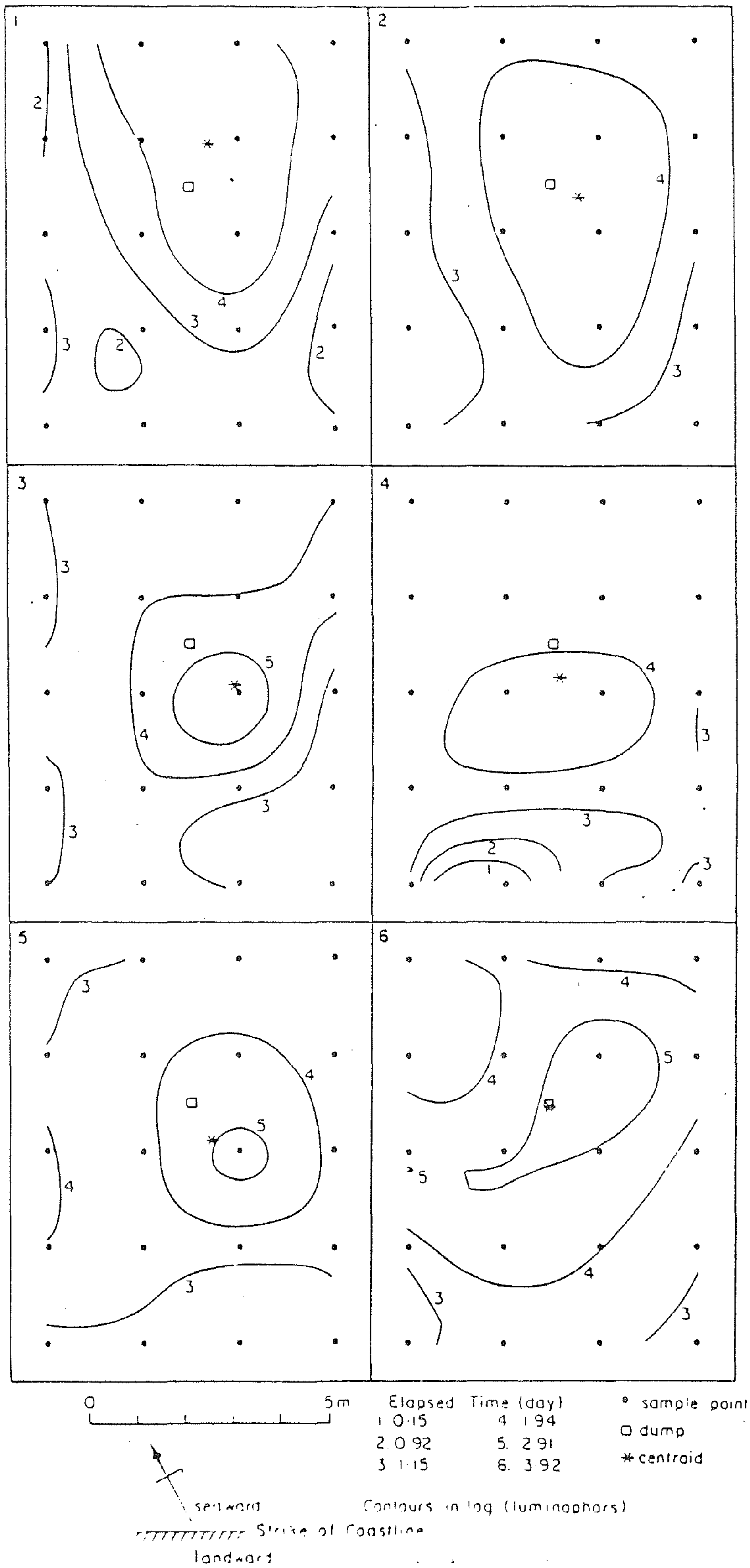


FIGURE 7.4 FLUORESCENT TRACER DISPERSION PATTERNS FOR EXPERIMENT 4.

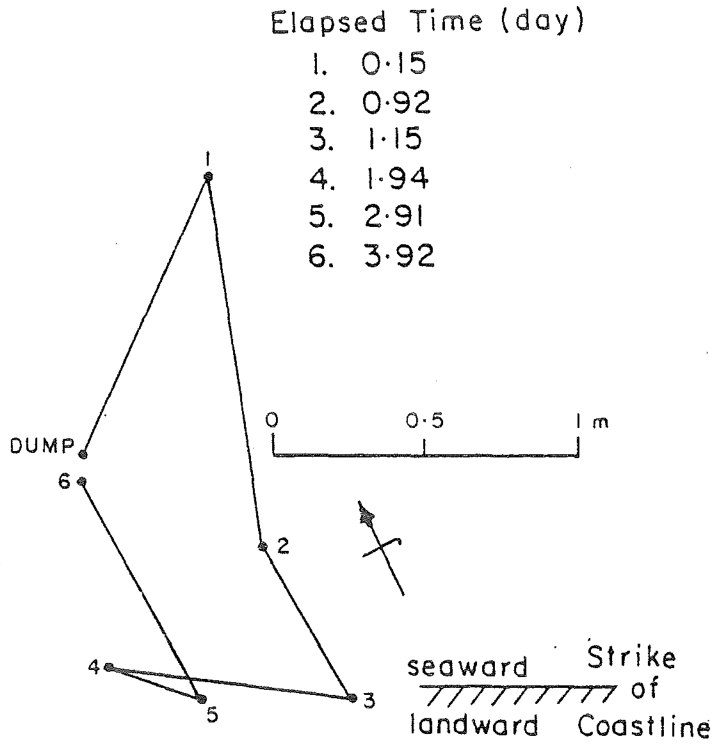


FIGURE 7.5 MOVEMENT OF THE FLUORESCENT TRACER CENTROID OVER TIME, EXPERIMENT 4.

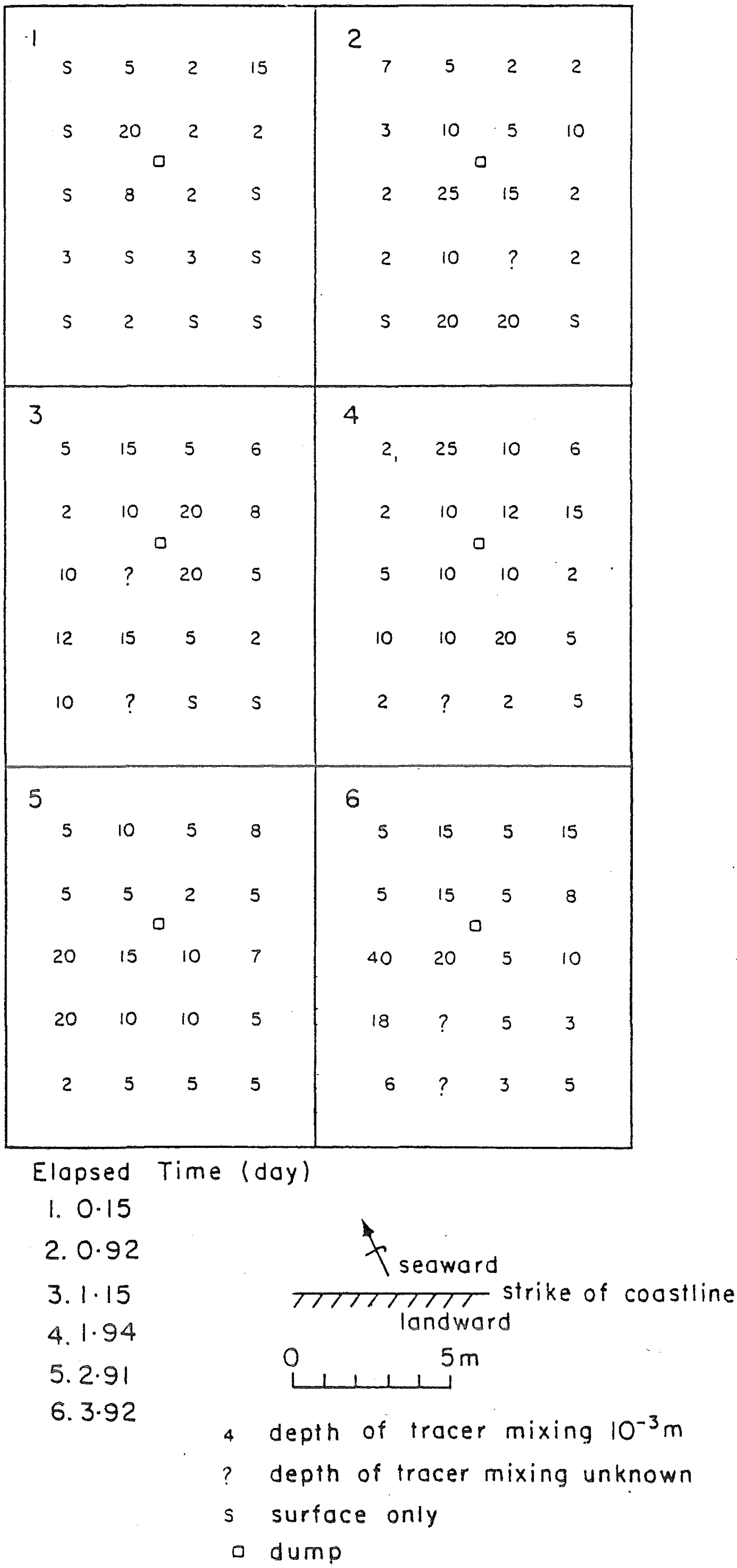


FIGURE 7.6 RECORDED MAXIMUM DEPTHS OF TRACER MIXING, EXPERIMENT 4.

and 3 and the minimum rate was 0.003 m^3 m^{-1} day^{-1} for sample run 5.

TABLE 7.5 TIME BETWEEN SAMPLE RUNS, CENTROID DISPLACEMENT, AVERAGE GRAIN VELOCITY V, AVERAGE THICKNESS OF THE MOBILE LAYER E AND SEDIMENT TRANSPORT RATE q, EXPERIMENT 4.

SAMPLE RUN NUMBER	TIME BETWEEN (day)	CENTROID DISPLACEMENT (m)	V MAGNITUDE (m day^{-1})	V DIRECTION (°TRUE)	E (m)	q (m^3 $m^{-1}$$day^{-1}$)
1	0.15	0.98	6.53	47	0.003	0.020
2	0.77	1.22	1.58	204	0.007	0.011
3	0.23	0.58	2.52	172	0.008	0.020
4	0.80	0.81	1.01	300	0.009	0.009
5	0.97	0.32	0.33	131	0.008	0.003
6	1.01	0.81	0.80	353	0.010	0.008

The sea was relatively calm throughout the experiment with only a surface chop and/or a very low swell occurring. No waves were large enough to be recorded by the wave recorder and so the only available wave data was from the visual observations. For this reason no attempt was made to look for statistically significant relationships between sediment transport rates and wave or wave-dependent parameters. Nine visual observations were made and the largest waves observed had a height of 0.3 m and a period of 10 s. On two occasions the sea was observed to be completely calm. On the other occasions the observed waves approached from the north to north-west quarter.

7.6.9.2 Europium Tracer

Standard addition curves for samples 2B, 2C and 3C from sample run 6 are shown in figure 7.7 and the calculated Eu concentrations for these samples are given in table 7.6. Unfortunately no sample of unlabelled sand from the study area had been analysed to assess the "background" level of Eu for the particular set of instrument settings that were used, which could influence the sensitivity of detection. Therefore these results could not be considered as reliable measurements of the concentration of Eu present in the samples. When the samples were re-analysed with all other samples from sample run 6 a sample of unlabelled sand from the study area was included to give a "background" concentration of Eu. These samples were analysed using separate standards and an example of one of the resulting calibration curves is shown in figure 7.8. The Eu concentrations obtained are shown in table 7.7, which includes the unlabelled and labelled sand samples. These figures showed that a "background" level of 12 $\mu g\ g^{-1}$ must be subtracted from all samples. If this is done then only samples 2B and 2C have levels of Eu above the "background" level. Therefore no dispersion pattern was drawn and no sediment transport data were calculated. Also, because sample run 6 had the highest concentrations of luminophors it was not considered worthwhile analysing samples from any other sample run.

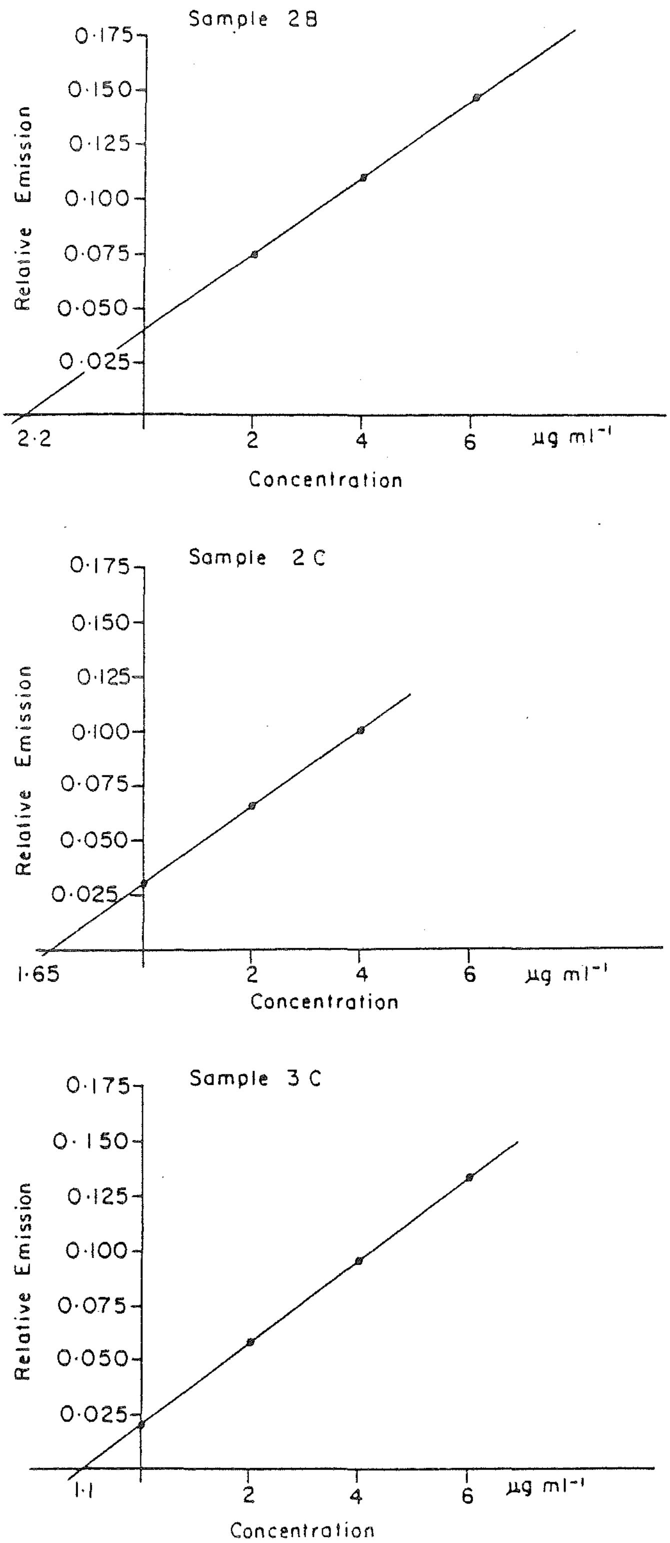


FIGURE 7.7 STANDARD ADDITION CURVES FOR EUROPIUM ANALYSIS OF SAMPLES 2B, 2C AND 3C FROM SAMPLE RUN 6, EXPERIMENT 4.

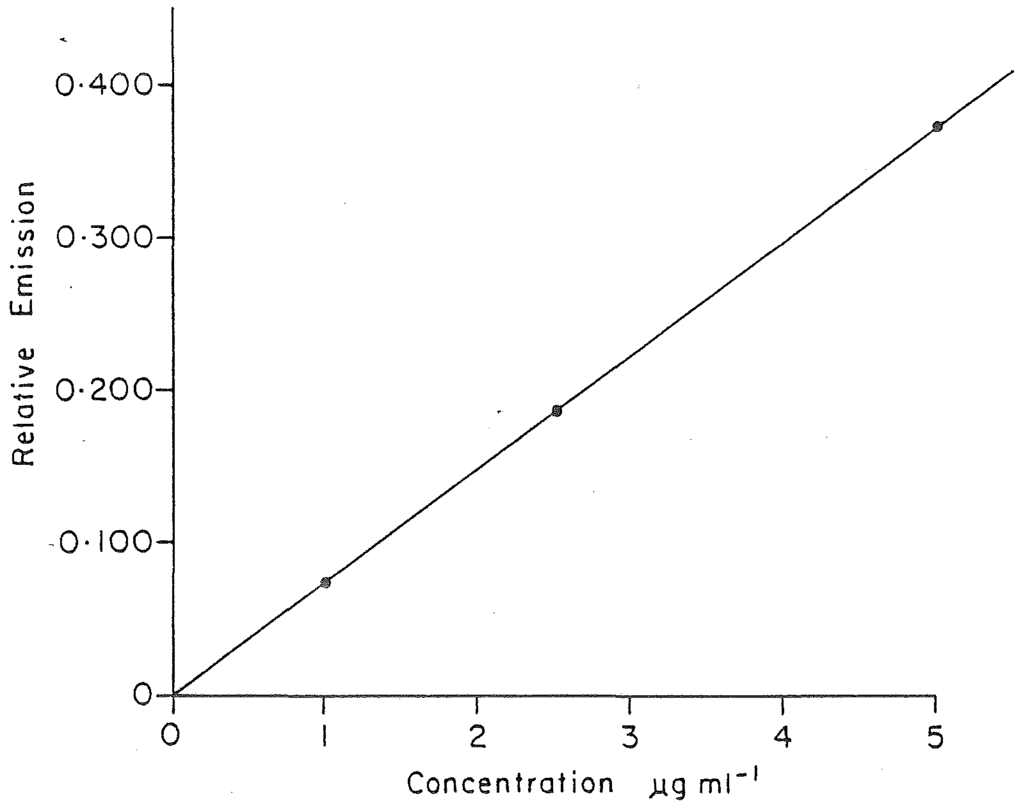


FIGURE 7.8 EXAMPLE CALIBRATION CURVE FOR THE ANALYSIS OF EUROPIUM CONCENTRATIONS IN SAMPLES FROM SAMPLE RUN 6 USING SEPARATE STANDARDS, EXPERIMENT 4.

TABLE 7.6 EUROPIUM CONCENTRATIONS IN SAMPLES 2B, 2C AND 3C FROM SAMPLE RUN 6. STANDARD ADDITION TECHNIQUE USED.

SAMPLE	WEIGHT	Eu CONCENTRATION	
	g	µg ml^{-1}	µg g^{-1}
2B	4.06230	2.20	54
2C	4.04995	1.65	41
3C	4.03925	1.10	27

TABLE 7.7 EUROPIUM CONCENTRATIONS IN SAMPLES FROM SAMPLE RUN 6. SEPARATE STANDARDS USED.

SAMPLE	1A	1B	1C	1D	1E	2A	2B
Eu CONCENTRATION µg g^{-1}	11	10	9	10	9	11	21
SAMPLE	2C	2D	2E	3A	3B	3C	3D
Eu CONCENTRATION µg g^{-1}	16	11	9	11	11	12	11
SAMPLE	3E	4A	4B	4C	4D	4E	
Eu CONCENTRATION µg g^{-1}	9	10	9	11	9	9	

SAMPLE	UNLABELLED	LABELLED
Eu CONCENTRATION µg g^{-1}	12	350

7.6.10 Comparison Of Fluorescent And Europium Tracers

An attempt was made to compare the concentrations of fluorescent and Eu tracer in samples 2B, 2C and 3C from sample run 6. The Eu tracer was assumed to have an Eu concentration of 338 $\mu g\ g^{-1}$ (see table 7.7). This value was divided by the three estimates of the number of grains per gram for the very fine fluorescent tracer sand (see section 4.7.3.3) to give three estimates of the amount of Eu per grain. These values were then multiplied by the measured fluorescent concentration (luminophors g^{-1}) to give estimates of the Eu concentration in the samples. The various estimates and the results are shown in table 7.8. The estimates using 3.6×10^5 grains per gram gave results very close to what was measured for samples 2B and 2C. The value of 0.9 $\mu g\ g^{-1}$ for sample 3C was probably below the detection limit of the analytical technique used.

TABLE 7.8 COMPARISON OF FLUORESCENT AND Eu TRACERS FOR SAMPLES 2B, 2C AND 3C FROM SAMPLE RUN 6.

ESTIMATED NUMBER OF GRAINS PER GRAM	μg Eu PER GRAIN	SAMPLE 2B		SAMPLE 2C		SAMPLE 3C	
		LUMINO-PHORS g^{-1}	$\mu g\ g^{-1}$	LUMINO-PHORS g^{-1}	$\mu g\ g^{-1}$	LUMINO-PHORS g^{-1}	$\mu g\ g^{-1}$
9.1×10^5 [1]	37×10^{-5}	9730	3.6	3479	1.3	985	0.4
7.5×10^5 [2]	45×10^{-5}	9730	4.3	3479	1.6	985	0.4
3.6×10^5 [3]	94×10^{-5}	9730	9.1	3479	3.3	985	0.9

[1] Used equation 4.8 and data from each sieve fraction

[2] Used equation 4.8 and mean grain size from sieved sample

[3] Counting of known dilutions

7.6.11 Discussion

The running of this experiment unfortunately coincided with a period of uncharacteristically warm weather for mid-November which tempted a number of people to partake in recreational activities in Caroline Bay. Swimmers, board sailers, yachts, power boats and water skiers were all observed in close proximity to the sampling grid. People in boats were observed pulling on the buoys marking the grid and on one occasion one of the buoys was cut off. Fortunately, apart from the loss of the buoy, the grid was not damaged. In addition, a number of boats were trawling in Caroline Bay each day at high tide and on one occasion the author had to stand and wave frantically from the shore in order to prevent a boat trawling right over the grid. These incidents highlight some of the problems associated with working in areas which are used for recreational purposes or for fishing. Many of the problems would be solved if a sample position fixing method that did not employ surface markers was used.

The method used to deploy the sampling grid for this experiment meant that once the first line was positioned correctly all other lines could be positioned correctly relative to it. The positions of the sample points were therefore fixed correctly and there were no problems of samples being too closely spaced or of large areas remaining unsampled.

One of the aims of this experiment was to compare the rates and directions of sediment movement as determined from both fluorescent and Eu tracers. Only the fluorescent tracer, however, provided enough data to enable sediment transport rates to be determined. The dispersion patterns of the fluorescent tracer did not show any consistent pattern of movement. This was also the case with the centroid movement which was both seaward and landward. For the final sample run the centroid was located almost back to the dump site.

The thickness of the mobile layer was estimated by averaging the maximum depths of tracer mixing for each sample run. The maximum depth of tracer mixing was used because it was easily measured. Because the depth of tracer mixing was generally very small throughout this experiment it would have been difficult to accurately determine tracer concentrations in a variety of depth increments to enable calculation of a concentration weighted depth for each sample. Figure 7.6 shows that the maximum depth of tracer mixing was quite variable over the grid but that it generally decreased with distance from the dump site.

The calculated transport rates were considerably lower than those found for very fine sand in experiments 1 and 2 within the same time period following tracer release. The low transport rates were obviously a function of both the location of the experiment site and the relatively calm conditions that occurred throughout the experiment. The fact that holes left where samples had been taken were not filled in completely during the experiment confirms that sediment transport rates were very low. The calculated transport rates are probably maximum values because the thickness of the mobile layer was calculated from the maximum depth of tracer mixing.

Because of the short duration of the experiment it would at first seem unlikely that the tracer had had sufficient time to become fully mixed into the mobile layer. Table 7.5 shows, however, that the estimated thickness of the mobile layer remained relatively constant after sample run 2 and this suggests that the tracer was fully mixed into the mobile layer.

No samples were taken at the dump site during the experiment but it was visually inspected by the author during each sample run. A considerable amount of fluorescent tracer was visible at the dump site throughout the experiment. For this reason no attempt was made to calculate the amount of tracer that could be accounted for from each sample run.

The tests that were carried out to assess the accuracy of the splitting and counting technique used for the fluorescent tracer analysis showed that an average error of about 10% can be expected. This error is therefore of the same magnitude as the measurement error found earlier for the Eu labelled sand.

The Eu tracer used in this experiment was much less sensitive than the fluorescent tracer and could only be detected in two samples from sample run 6. The lack of sensitivity can be attributed to the detection technique used and to the background level of Eu. The detection technique could have been improved by using the purification procedure outlined by Ditchburn and McCabe (1982). However, if this technique had been used sensitivity would still have been limited by the background level of Eu. Another factor reducing the sensitivity was the level of Eu on the labelled sand which was found to be much lower than the level measured in the samples prepared in the laboratory tests. The reason for this difference is not known but it is probably related to the vastly different amounts of sand that were labelled in each case.

A considerable quantity of fluorescent tracer was visible at the dump site throughout the experiment. It is probable that a similar quantity of Eu also remained at the dump site throughout the experiment. If more of this tracer had moved over the grid during the experiment Eu tracer may have been detected in more samples. In other words, if sediment transport rates had been higher the Eu tracer may have produced better results.

One important point that arose during the analysis of the Eu tracer was that a sample of unlabelled sand from the experiment site should always be included in the analysis to provide a "background" level. Theoretically, if standards are used this "background" level should be the real background level. However, if the instrument is set slightly off the peak in the spectrum the detection will be less sensitive and some noise may be introduced. The "background" level will then be a function of the instrument settings used. The instrument used in this experiment has a very coarse adjustment for the wavelength and slightly different settings produced marked variations in the results.

When volumetric samples are collected for sediment tracer studies it is important to ensure that the samples taken do not extend too far below the limit of tracer mixing because this will reduce the concentration of tracer in the sample. This factor becomes increasingly important as the sensitivity of tracer detection decreases and it was therefore much more important for the Eu tracer than for the fluorescent tracer. This problem was overcome for this experiment by retaining the samples as cores until they were inspected and then keeping only that portion of the sample that contained tracer. This was only possible because fluorescent tracer had been used and if Eu tracer was used by itself an arbitrary depth would have to be chosen. The depth chosen could have a large influence on the success of the experiment. In addition, if the depth of tracer mixing was to be determined for the Eu tracer separate cores would have to be taken and discrete depth intervals analysed. The problems of undertaking this kind of analysis when the depth of mixing is small have already been pointed out.

The only comparison that was made between the results from the fluorescent and Eu tracers was for samples 2B, 2C and 3C from sample run 6. Using the lowest estimate of 3.6×10^5 grains per gram good agreement was obtained between the concentrations of fluorescent and Eu tracers present in these samples. It seems reasonable to expect that the concentrations would be in fairly close agreement because the tracers were thoroughly mixed before release. This result indicates that the lowest estimate may be the best estimate of the number of grains per gram for the tracer that was used.

Preparation of the Eu tracer was considerably more expensive and time consuming than preparation of the fluorescent tracer. No special equipment was required, however, whereas a specially designed dyeing machine was used to produce the fluorescent tracer. Tracer release and sampling was the same for both types of tracer. Analysis of the Eu tracer was much more time consuming than analysis of the fluorescent tracer and required greater expertise and specialised equipment. Considering these comparisons and the much greater sensitivity of the fluorescent tracer it appears on balance that the fluorescent tracer type was the better of the two. It is therefore recommended that fluorescent tracer be used wherever possible. When fluorescent tracer cannot be used because the sediment is too fine, or for some other reason, both radioactive and Eu tracers should be considered. If Eu tracer was to be used, however, the sensitivity would have to be increased. The sensitivity would be increased if the level of Eu on the labelled sand was increased, a greater quantity of Eu tracer was released or if the background level of Eu was lower.

7.7 SUMMARY AND CONCLUSIONS

An alternative tracer type to fluorescent tracer was sought for nearshore sediment transport studies in New Zealand. Radioactive tracers were investigated and it was found that they could be used in New Zealand but that they were not feasible for this study. A chemical tracer was then tested in the laboratory and used in a small scale field experiment along with fluorescent tracer. Sand was labelled with Eu using the method of Malone (1969, p. 17) and atomic emission analysis was used for detection. Atomic emission analysis was used because neutron activation analysis was not available and it was the best remaining option. The Eu tracer lacked sufficient sensitivity in the field experiment and could only be detected in two samples. A considerable amount of tracer is assumed to have remained at the dump site throughout the experiment and better results may have been obtained if more of this material had moved over the sampling grid.

After comparing the fluorescent and Eu tracers it was decided that the fluorescent tracer was the better of the two and should be used wherever possible. If fluorescent tracer is not suitable for some reason both radioactive and Eu tracer should be considered. Eu tracer should only be used if the sensitivity is improved. This would occur if the background level of Eu was lower, more Eu tracer was released or the level of Eu on the labelled sand was increased.

The low sediment transport rates calculated from the fluorescent tracer was due to the low energy conditions occurring at the experiment site throughout the experiment. Because no direct comparison with wave conditions was possible these calculated rates cannot be extrapolated over a longer time period.

CHAPTER VIII

EVALUATION OF TECHNIQUES AND RESULTS

8.1 INTRODUCTION

Chapters 4-7 have described experiments using artificial sediment tracers that were undertaken during the present study. These experiments were designed to obtain data on nearshore sediment transport in the study area. In two cases the experiments were also designed to evaluate the use of a particular artificial tracer type. This present chapter seeks firstly to review the practical application of the artificial tracer technique in studies of nearshore sediment transport; and secondly, to evaluate the results from the experiments in terms of nearshore sediment transport in the study area. Theories of wave-induced nearshore sediment transport are then reviewed in the light of the results from the present study. In addition, some applied aspects arising from the results are considered.

8.2 THE PRACTICAL APPLICATION OF THE ARTIFICIAL TRACER TECHNIQUE IN THE NEARSHORE

This section is concerned with the practical application of the artificial tracer technique in the study of nearshore sediment transport. This includes determining the extent to which the various requirements and assumptions can be satisfied. Only the spatial integration method is considered because, as outlined in section 1.4.7.2, both the time integration method and the steady dilution method are not suitable for measuring nearshore sediment transport. No attempt is made to evaluate the theoretical basis of the spatial integration method.

8.2.1 Tracer Type

The first step involved in any artificial tracer study is to choose the tracer type. Six types were identified in section 1.4.7.2 based on their distinguishing property or characteristic. Three of these have been used during the present study. A magnetic tracer (ironsand) was used in experiment 1; a chemical tracer (Eu labelled sand) was used in experiment 4; and fluorescent tracer was used in all experiments. The tracer types not used during this study were foreign, coloured and radioactive.

Five criteria that should be satisfied by an artificial tracer were listed in section 1.4.7.2. The three tracer types used during this study are now reviewed in terms of these criteria.

a) Hydraulic Behaviour All three tracer types used during this study were composed of natural beach sediments. The magnetic tracer, ironsand, was not treated in any way. Production of the fluorescent and chemical tracers, however, involved labelling the natural beach sediments. The respective labelling processes were not thought to significantly alter the hydraulic behaviour of the sediments.

In some cases the tracers may have represented only a portion of the total sediment population at a site because of size or specific gravity differences. For example, the magnetic tracer was only representative of the transport of equivalent heavy minerals and the fluorescent tracer used during experiment 2 was only representative of the transport of the 75.5% of the native seafloor sand which lay between 2.30 ϕ and 3.65 ϕ.

b) Sensitivity The fluorescent tracer type could be easily detected in the samples, even when concentrations were low. Errors in the detection procedure were detailed in sections 4.7.1 and 7.6.8. Both the magnetic and chemical tracers lacked sufficient sensitivity to enable detection when concentrations were low. Analysis was relatively time consuming for all of the tracer types.

c) Cost and Availability Both the fluorescent and magnetic tracers were inexpensive and available in relatively large quantities. The chemical tracer, however, was expensive and only a small quantity could be produced.

d) Safety Hazard None of the tracer types used presented a hazard to either the public or to marine life. Cadmium labelled sand had been considered as a chemical tracer. It was not used, however, because of the extreme toxicity of cadmium.

e) Identification Property All of the tracer types used during this study retained their identification property for the duration of the respective experiments.

For studies of fine nearshore sands in New Zealand fluorescent tracer is considered to be the best tracer type. For sediments finer than very fine sand both radioactive and chemical tracers should be considered. If Eu labelled sediment were to be used, however, the sensitivity would have to be improved in one of the ways described in section 7.6.11.

The situation for coarse sediments is slightly different. Fluorescent dye was used to label coarse sediments for experiments 1 and 3. The coarsest particles (pebbles) could, however, have more simply been painted with a non-fluorescent paint and then treated as coloured tracers. This would have made no difference to experiment 1 but would have eliminated the night time searches during experiment 3.

In section 4.7.4.2 it was noted that *in situ* detection of coarse particles would have been a definite advantage during experiment 1 because the number of coarse particles released was very much smaller than the number of fine particles released. Therefore even when the concentration of tracer was high the number of tracer particles in a grid sample was small. *In situ* detection could be provided by radioactive tracers. Another possible option not previously considered would be to use a magnetic tracer such as the aluminium pebbles used for a beach tracing experiment by Wright, Cross and Webber (1978, 1979). There is no apparent reason why an underwater metal detector could not be used to locate such particles on the seafloor. The metal detector could be either diver operated or operated from a boat, and could be used for spot measurements or, alternatively, towed on some kind of sled. One limitation of this method would be that only one size of sediment could be traced because, unless each particle was recovered, there would be no way of distinguishing size. Therefore if a seafloor tracing experiment is to be undertaken using pebbles it is recommended that both radioactive and magnetic tracers be considered so that in situ detection would be possible.

8.2.2 Quantity Of Fluorescent Tracer Required

The previous section has recommended the use of fluorescent tracer for experiments involving fine nearshore sands in New Zealand. One question of prime importance in such experiments is how much tracer should be used? If insufficient tracer is released concentrations may become too low to enable detection for the required time period. On the other hand, if too much tracer is released some of it may become buried at the dump site. If this tracer is subsequently uncovered it may act as a new source of tracer and cause an apparent movement of the tracer centroid back towards the dump. Section 5.9.2 suggests that this may have occurred during experiment 2.

Table 8.1 lists the amounts of tracer released and the duration of sampling for all of the seafloor fluorescent tracing experiments that could be found in the literature. Included in the table are the figures for experiments 1 and 2. The quantity listed for experiment 1 is the quantity of very fine sand used. This figure was chosen because the seafloor sand at the site was mainly very fine sand. The figures in table 8.1 show that there is an approximate relationship between the duration of sampling and the quantity of fluorescent tracer released. An exact relationship would not be expected because sampling does not necessarily continue until all tracer has left an area and because the experiments were carried out under a range of energy conditions.

TABLE 8.1 QUANTITIES OF FLUORESCENT TRACER RELEASED AND DURATION OF SAMPLING FOR SEAFLOOR FLUORESCENT TRACING EXPERIMENTS.

AMOUNT RELEASED (kg)	DURATION OF SAMPLING (DAY)	REFERENCE
1	0.04	Miller and Komar (1979)
5.9	0.19	Ingle (1966)
6.5	0.1	Ingle (1966)
16.2	5	Jolliffe (1963)
45	174	Moore and Fry (1967)
51	70	this study, experiment 1 very fine sand
90	97	Brattelund and Bruun (1975)
337	21	this study, experiment 2
750	165	Lees (1981)

The best recommendation that can be made if a fluorescent tracing experiment is to be undertaken is that the figures in table 8.1 be used as a guide to be quantity of tracer required.

8.2.3 Sampling Grid

The spatial integration method is based on successive surveys of the spatial distribution of tracer. A sampling pattern or grid must therefore be established. The size of the area requiring sampling is a function of the amount of tracer released, the intended duration of the experiment, and the sediment transport rate. For tracer types that require the collection of samples, the size of the sampling grid established and the density of sampling points will be a function of the amount of time available for sampling and the available position fixing methods. The position fixing methods available for the present study were discussed in section 4.4. A rope grid placed on the seafloor was chosen for experiment 1 and was re-used for experiment 2. An alternative rope grid was used for experiment 4. The rope grids proved to be excellent and allowed fast, precise, position fixing during sample collection. They were designed for sample collection by divers, whose role in sediment tracing experiments is discussed in the next section. The rope grids ensured that the absolute position of each sample was accurately fixed throughout the experiment. This is particularly important because the sediment transport rate is based on the movement of the tracer centroid between sample runs. Uncertainties are therefore introduced if the absolute position of the samples cannot be fixed exactly for each sample run. This was the case during radioactive tracing experiments carried out by Lavelle et al. (1978) on the Long Island, New York, inner shelf at water depths of 20-22 m. Surveys of the tracer distributions were carried out using a detector towed behind a boat. The position of the detector was determined using a "Raydist" navigation system which had a resolution of ± 10 m. This enabled the relative position of the detector during each sample run to be determined with a precision of ± 10 m. The absolute position, however, could only be determined within the accuracy of the initial calibration of the system which was based on sextant fixes. In some experiments the surveys showed that the point of highest tracer concentration had shifted although no systematic explanation could be found for the movement using current data. It was concluded that the apparent shifts in the position of highest tracer concentration in these cases were simply due to the errors in the calibration of the position fixing system. Lavelle et al. (1978) recommended that the positions of the release points and the surveys should be determined more accurately.

The radial grid used for experiments 1 and 2 had three disadvantages. Firstly, the area it covered was insufficient for the finer sand sized sediments. This disadvantage could have been overcome by using an alternative position fixing method to sample the area surrounding the grid. Secondly, it was difficult to lay the lines on the correct headings. This disadvantage could have been overcome by laying the grid in the same way that the grid for experiment 4 was laid, that is, by laying one line and then orienting all other lines relative to this by using triangulation. This would have been a difficult job because of the size of the radial grid but it would have been possible provided the weights were attached after placement. Then, if the orientation of the first line was known, the orientation of all other lines could have been determined. Thirdly, the buoys used to mark the grid can be fouled by boats, as was the case during experiment 2. Although it is unlikely that this problem can be overcome completely it can be minimised by notifying the skippers of all boats likely to pass through the area.

The rope grids used in this study were not symmetric about the dump point. When they were laid they were oriented according to the expected direction of maximum transport. There were, however, sample points in all directions around the dump site to allow for some transport in all directions. Courtois (1973, p. 73) states:

> ... we ourselves have long since abandoned all preconceived notions concerning the predictable displacement of a tracer, so much has nature accustomed us to finding the contrary of what we expected.

Therefore even if the predominant transport direction is known before the experiment, allowance should be made for some transport in any and all directions.

8.2.4 Release And Sampling

Divers were used during the present study for both the release of tracer and sample collection. The divers were able to ensure that all tracer was released exactly at the dump site and that all samples were collected at the exact positions marked on the grid. Neither the release nor the sampling could have been as accurate if carried out from a boat. Vernon (1966) found that sampling from a boat was difficult, time-consuming, and not sufficiently accurate for sampling close to the release point. He therefore abandoned this method in favour of divers. In addition, during the present study divers were able to control exactly how deep each grid sample was taken. Much less control would have been possible if sampling had been carried out from a boat.

A diver can not only increase the precision of release and sampling but can also provide information that is otherwise unobtainable (Ingle 1966). This can include information on such things as the nature of the bottom and the approximate size of any bedforms that are present.

Poor underwater visibility and strong currents are both thought to restrict the use of divers for sediment tracing experiments (Kidson and Carr 1962; Noda 1971) and have been quoted directly as reasons why divers were not employed during particular experiments (Jolliffe 1963; Lees 1981). Divers were, however, used successfully during the present study in an area that was characterised by poor underwater visibility and by wave-induced oscillatory currents. Visibility was not required for either the tracer release, the location of sample points or the taking of samples, although initially if visibility was poor it was difficult to find the correct sampling tube. This problem was overcome during experiment 2 with the cartridge belt system used by the author. Poor visibility alone should not therefore restrict the use of divers for sediment tracing experiments.

The problem of strong currents cannot be solved as easily as the problem of poor visibility. A rule of thumb is that divers find it difficult to do precise work in currents greater than 50 cm s^{-1}. The rope grid used during experiments 1 and 2, however, enabled samples to be collected on occasions when the wave-induced oscillatory currents were sufficient to move a diver approximately 2 m in either direction under a wave. In addition, during storms when diving is impracticable, the collection of samples from a boat would also be impracticable. The present study area was not subjected to strong tidal currents. However, it is estimated that the use of a rope grid would enable sampling in all but the strongest tidal currents. It is therefore concluded that in many cases the problem of strong currents may not render diving impracticable.

It is recommended that divers be used during sediment tracing experiments wherever possible, irrespective of the method of sample position fixing.

Because surface samples would only retrieve a small portion of the total tracer at a site after initial mixing had begun volumetric samples should be collected for all nearshore sediment tracing experiments. During the present study samples were collected in short PVC core tubes. Sample taking was improved during the study by adding a piston to each tube, by turning out the end caps so that they fitted flush with the end of the tube and by drilling holes in the end caps to enable water to escape during capping. After these improvements were made each grid sample could be retained intact. Because fluorescent tracer had been used during the experiments it was possible to measure the maximum depth of tracer mixing. This meant that separate core samples were not required. It also meant that it was possible to discard the section of core below the maximum depth of mixing. This is important because it enables tracer concentrations to be kept as high as possible. It is often tracer concentration and not the absolute amount of tracer that limits the detection sensitivity.

Not all samples taken with the core tubes were successful. One way of achieving a higher success rate was suggested in section 5.9.3. This simply involved using clear plastic core tubes so that the samples could be inspected immediately after they were returned to the surface. If a sample was found to be unsatisfactory for some reason (for example, if it contained excess water) it could be re-taken immediately. With this modification it is believed that the core tubes would provide an ideal means of collecting samples for sediment tracing experiments. They are inexpensive and easy to construct and can be operated by a diver working in conditions of zero visibility.

One assumption made for a sediment tracing experiment is that the behaviour of the tracer is independent of the manner in which it was introduced. If the tracer is simply dumped on the surface of the seabed, as was the case during the present study, long-term transport estimates should be based on samples collected after the tracer has had sufficient time to become fully mixed into the mobile layer. The time required for mixing and the thickness of the mobile layer are both dependent on the magnitude of currents at the seabed. The results from this experiment suggest that when the currents are relatively weak the thickness of the mobile layer is relatively small and mixing time is relatively short. Weak currents can occur either as a function of the site, for example if it is located in deep water, or as a function of low wave energy. If the latter is the case results based on samples collected during the period of weak currents will not be representative of the long-term. This was thought to be the case for experiment 4.

Calculated sediment transport rates decreased markedly after the first four sample runs during experiment 1 and after the first sample run during experiment 2. It was therefore assumed that complete mixing took from 5 - 10 days for experiment 1 and from 2 - 5 days for experiment 2. Heathershaw and Carr (1977) estimated mixing times of 2 - 7 days for radioactive tracing experiments carried out in Swansea Bay, U.K. Therefore, in areas subjected to relatively strong current action it is recommended that at least 5 days be allowed for complete mixing of tracer into the mobile layer.

8.2.5 Calculation Of Sediment Transport Rates

During the present study sediment transport rates were calculated using the spatial integration method. This method is based on both the average grain velocity, which is calculated from positional shifts of the tracer centroid, and the estimated thickness of the mobile layer. In section 1.4.7.2 it was noted that the thickness of the mobile layer is a critical parameter because it is directly related to the calculated sediment transport rate, and that Komar and Inman (1970) have described it as the most uncertain of all parameters measured. Different measures of the thickness of the mobile layer were discussed in section 5.9.3. During the present study an average concentration weighted depth was used for experiment 1 while the average maximum depth of tracer mixing was used for experiments 2 and 4. In experiments 2 and 4 the calculated sediment transport rates were assumed to be upper limits to the range of possible values. This study has not attempted to test thickness parameters or to develop new ones. Instead it has concentrated on developing sampling tubes that retain all grid samples as cores. These sampling tubes could be used in future work to develop new thickness parameters.

Section 1.4.7.2 outlined two assumptions that must be made when using the spatial integration method. These are:

a) That sediment transport is more or less uniform in the study area and,

b) That tracer behaviour is independent of the manner in which it was introduced.

Tracer studies may lead to the wrong conclusions if the first assumption is not satisfied. This fact was demonstrated by Price (1969) who developed an arithmetic model showing that tracer would tend to move from an area of low diffusion toward an area of high diffusion even if there was no net transport. On a beach, for example, tracer would tend to move towards the breaker zone because this is the area of highest diffusion, irrespective of whether or not there was a net movement of beach material in this direction. Experiments 1 and 2 during the present study were carried out approximately 1.4 km and 2 km offshore respectively. There is no reason to suspect that transport was not uniform at the experiment sites and it is therefore concluded that the assumption of uniform transport was satisfied. Experiment 4 in Caroline Bay was much closer to shore. At low tide the site was, however, still approximately 100 m from the beach. In view of this and the small sampling area it is believed that the transport was uniform in the area and that the assumption was satisfied.

The second assumption was discussed in the previous section. It is easily satisfied by allowing sufficient time for tracer to become fully mixed into the mobile layer.

A further requirement outlined in section 1.4.7.2 was that all of the tracer grains released should be accounted for. There is no standard method for determining how many tracer grains can be accounted for. For fluorescent tracer studies, however, the accounting procedures are usually based on the assumption that the amount of tracer in each sample yields an estimate of the total amount of tracer in the region from which the sample was taken (see for example Inman et al. 1981; Kraus, Farinato and Horikawa 1981).

With the exception of the granule and pebble size classes for experiment 1, the accounting methods used during the present study were dependent on the number of tracer grains per gram. As explained in section 4.7.3.3 this was because the initial amount of tracer released was weighed whereas analysis involved counting of tracer grains. Determining the number of grains per gram is difficult, especially for fine sands. This fact was illustrated in section 4.7.3.3 where several methods were used to determine the number of grains per gram for very fine tracer sand. The resulting values ranged from 3.6×10^5 to 1.59×10^6 grains per gram. The lowest estimate was based on the counting of known dilutions of tracer grains. Based on the comparison of the fluorescent and Eu tracers during experiment 4 it is believed that this lowest estimate may be the best value (see sections 7.6.10 and 7.6.11).

Accounting procedures for experiment 1 were further complicated by the large size range of tracer used and by the fact that only the concentration of tracer in a sample was measured, and not the total amount. It is therefore difficult to place too much confidence in the figures calculated for experiment 1. For experiment 2 only one size of tracer was used and the total number of tracer grains in a sample was determined. The estimated accounting values are therefore considered to be more reliable for this experiment. The calculated values, based on the dilution estimate of the number of grains per gram, ranged from 39 - 128%. Published figures of the percentage of tracer accounted for also have a considerable range. For example, Inman *et al.* (1981) calculated values ranging from 39 - 77% and Kraus, Farinato and Horikawa (1981) calculated values ranging from 10 - 102%.

Greer and Madsen (1979) point out that interpreting the significance of results from an accounting procedure is difficult. On occasions, for example, when less than 100% of the tracer is accounted for, it is not known whether this is due to errors in the analysis and/or accounting procedure, or whether tracer particles moved outside the sampling area. On several occasions during the present study greater than 100% of the tracer was accounted for, showing that errors must be present in either the analysis or accounting procedure, or in both. In addition, the open contours that appear on many of the dispersion patterns suggest that some tracer grains did leave the sampling area and therefore could not be accounted for. It is not known to what extent this affects the results.

Additional research is needed to establish a standard accounting procedure and to determine the minimum percentage of tracer that must be accounted for, using this procedure, for the results to be significant.

In summary, the first two assumptions made for an artificial tracing experiment employing the spatial integration technique can be satisfied in the nearshore. There is, however, some uncertainty regarding the significance of the requirement that all tracer grains be accounted for. It is therefore concluded that artificial tracing experiments can be used to obtain estimates of nearshore sediment transport rates and that results obtained during the present study can provide reliable estimates of both sediment transport rates and patterns within the study area. It is believed that these estimates are as good as, or better than, any estimates that could have been obtained using any of the other techniques outlined in section 1.4.

8.3 EVALUATION OF RESULTS

This section evaluates the results from experiments 1, 2 and 3 in terms of sediment transport in the study area. The results from experiment 4, which was undertaken largely to test the use of an alternative tracer type, are not considered in the evaluation because they are not deemed to be representative of sediment transport in the long-term.

Evidence from the bathymetry of the study area (section 3.2) and observed changes in the seabed elevation at site C (section 3.5) suggested that large scale bedforms may exist in the study area and therefore that some of the nearshore sediment transport may occur through the migration of these bedforms. No results from the experiments, however, give any indication of the presence or otherwise of large scale bedforms or of their possible role in nearshore sediment transport.

8.3.1 Long-Term Sediment Transport Rates

Wave and wave-dependent parameters calculated from the full set of wave data were used to estimate long-term sediment transport rates using the relationships presented in tables 4.12 - 4.16. These rates were calculated for three water depths. These were the average water depths at the sites of experiments 1 and 2, 7.6 and 12.2 m respectively, and an intermediate water depth of 10.0 m.

Many of the relationships that had been found were between average grain velocity and wave or wave-dependent parameters. In these cases a long-term average grain velocity was calculated. This value was then used with an estimated thickness of the mobile layer to calculate a long-term sediment transport rate from equation 4.4. For the 7.6 m water depth the estimated thickness of the mobile layer was 0.07 m. This was the average estimated thickness of the mobile layer for very fine sand, fine sand, medium sand and very coarse sand for the final three sample runs of experiment 1. This value compares well with the depth of disturbance value of 0.11 m measured at site C in a water depth of 6.7 m (see section 3.5). For the 12.2 m water depth the estimated thickness of the mobile layer was 0.06 m. This was the value measured for the final sample run of experiment 2. Because no data on the thickness of the mobile layer were available for the 10.0 m water depth an intermediate value of 0.065 m was chosen.

Long-term sediment transport rates were calculated for very fine sand, fine sand, medium sand, very coarse sand and granules for each of the three water depths, although not all of these sizes are necessarily present on the seafloor at each of these depths. Because of the limited number of data points in the relationships the calculated rates should be treated as order of magnitude estimates only.

In cases where several relationships had been found between average grain velocity or sediment transport rate and wave or wave-dependent parameters, the relationship involving $\bar{U}_{max1}$, the average maximum linear current, was used. This was done because it was necessary to use one of the current parameters for all calculations for the 10.0 and 12.2 m water depths.

The average current parameters, calculated from the full set of significant wave height and period data using both linear and second order wave theories (see appendix 2), are shown in table 8.2. The parameters are defined in table 4.3.

TABLE 8.2 AVERAGE CURRENT PARAMETERS CALCULATED FROM THE FULL SET OF WAVE DATA FOR THREE WATER DEPTHS. THE PARAMETERS ARE DEFINED IN TABLE 4.3.

WATER DEPTH (m)	$\bar{U}_{max1}$ (cm s^{-1})	$\bar{U}_{max2}$ (cm s^{-1})	$\bar{U}_{max3}$ (cm s^{-1})	$\bar{U}_{max4}$ (cm s^{-1})
7.6	49	8	57	41
10.0	41	4	45	37
12.2	36	2	38	34

The calculated long-term sediment transport rates are presented in table 8.3. For very fine and fine sand the relationships used were for the first four sample runs of experiment 1 and it was therefore necessary to reduce the

TABLE 8.3 ESTIMATED LONG-TERM SEDIMENT TRANSPORT RATES.

SIZE CLASS	SEDIMENT TRANSPORT RATE ($m^3\ m^{-1}\ day^{-1}$) WATER DEPTH			COMMENTS
	7.6 m	10.0 m	12.2 m	
Very Fine Sand	0.028	0.015	0.008	Used the relationship between V and $\bar{U}_{max1}$ given in table 4.12.
Fine Sand	0.017	0.010	0.005	Used the relationship between V and $\bar{U}_{max1}$ given in table 4.13.
Medium Sand	0.084	0.032	0.006	Used the relationship between q and $\bar{U}_{max2}$ given in table 4.14.
Coarse Sand	0.01-0.02			From table 4.7
Very Coarse Sand	0.028[1]	0.016	0.008	Used the relationship between V and $\bar{U}_{max1}$ given in table 4.15.
Granules	0.014	0.009	0.007	Used the relationship between V and $\bar{U}_{max1}$ given in table 4.16.

[1] This rate was calculated using both the relationships between q and $\bar{H}_s$ and between V and $\bar{U}_{max1}$. The rate given is the average of these two.

average grain velocities before calculating long-term sediment transport rates. The required reductions were calculated from table 4.10, which presents numerical mean average grain velocities for the first four sample runs and for the final three sample runs of experiment 1. No relationships for coarse sand had been found. Results from experiment 1, however, suggest that the long-term sediment transport rate at a water depth of 7.6 m will be of the order of 0.01 - 0.02 m^3 m^{-1} day^{-1}.

The estimated rates for medium sand appear to be too high when compared to the other values for these water depths. They also appear to be too high when compared to the values calculated for medium sand for the final three sample runs of experiment 1 (see table 4.6). The relationship used to calculate the long-term rates for medium sand was the only relationship used where the input values fell outside the range of values used to obtain the relationship. It was also the only relationship which used $\overline{U}_{max2}$, as an input. It is therefore concluded that the long-term rates presented in table 8.3 for medium sand are not representative of actual long-term rates.

The values in table 8.3 show again that there is no simple relationship between sediment size and transport rate. The values also suggest that if any relationship does exist it may be depth dependent because the relationships between the values vary with water depth.

Kirk (1978) presents the only sediment transport rate for Timaru that is comparable with the long-term estimates given in table 8.3. From an artificial tracer study (described in section 2.3) Kirk calculated a sediment transport rate of 0.46 m^3 m^{-1} day^{-1} for very fine sand in a water depth averaging 8 m. This is greatly in excess of the rate of 0.028 m^3 m^{-1} day^{-1} calculated from the present study for very fine sand in a water depth of 7.6 m. Kirk's rate was calculated from tracer samples collected 92.5 h after the tracer release. Results from experiment 1 suggested that it took in excess of 4 days for complete mixing of the tracer into the mobile layer at a site approximately 600 m to the south-west of the site of Kirk's experiment (see sections 4.7.4.6 and 8.2.4). It is concluded that Kirk's rate was calculated from samples collected before the tracer had become fully mixed into the mobile layer and is therefore not representative of the long-term rate. This explains the large difference between Kirk's estimate and the estimate made during the present study.

8.3.2 Patterns Of Nearshore Sediment Transport In The Study Area

Experiment 1 was located at a site approximately 2 km to the north of Timaru Harbour and 1.4 km offshore, in a water depth averaging 7.6 m (see fig. 3.8). Results from the experiment showed that sediments ranging in size from very fine sand to granules moved predominantly in a landward direction at the site. The index of net movement calculated from the dispersion patterns showed that there was an increasing tendency for landward movement with increasing grain size (fig. 4.18).

Experiment 2 was located immediately south of Timaru Harbour entrance channel approximately 2 km offshore, in a water depth averaging 12.2 m (see fig. 3.8). The results from the experiment, which were strictly applicable to the 75.5% of the native sediment at the site lying between 2.3 ϕ and 3.65 ϕ, showed a net landward movement of sediment. There was, however, some variability in the direction of movement as indicated by the dispersion patterns which showed a northward movement superimposed on the net landward movement.

The hydraulic conditions in the study area were described in section 3.4. It was suggested that wave-induced oscillatory currents dominated in the area and were therefore the primary agents responsible for sediment transport. It was concluded in section 3.7 that sediment should move predominantly north-westwards and shorewards. The patterns of movement outlined above for experiments 1 and 2 support the suggestion that wave-induced currents dominate sediment transport in the study area. Sediment generally appeared to move in the direction of wave advance. The significant relationships found between average grain velocity or sediment transport rate and wave or wave-dependent parameters provide further supporting evidence. Under these transport conditions longshore movement would occur only as a result of waves approaching the coast at some angle. There would therefore be greater potential for longshore movement in relatively deeper water where waves are less refracted and so can be expected to approach from a greater range of directions. Wave direction data collected during the present study at a site approximately 2.5 km offshore showed a greater range in predominant wave directions than data previously collected at the shore. It was suggested in section 3.4.4.3 that less wave refraction at the offshore site may have been one reason for this difference. A greater range in wave directions in deeper water could explain why there was greater variability in the movement of very fine sand during experiment 2 than during experiment 1.

Other tracer studies in the nearshore have found that sediment movement was in the direction of wave advance. Sato, Ijima and Tanaka (1963) carried out radioactive tracing experiments off the coast of Japan. On open coasts they found that the direction of sand movement coincided with the general direction of wave advance unless tidal currents exceeded 50 - 100 cm s^{-1}. Vernon (1966) carried out a number of fluorescent tracing experiments on the continental shelf off California. The most common pattern of movement found by Vernon was a slow onshore transport of all grain sizes tested.

In summary, the results from experiments 1 and 2 indicate a wave-induced net landward movement for all grain sizes tested. However, with the exception of Caroline Bay, all of the beaches in the study area are composed only of coarse sediments. Experiment 3 showed that the coarse grained beaches could receive sediment from the seafloor. It can therefore be assumed that coarse material moving landward on the seafloor will move onto the beaches. The question is, what happens to the finer sediments that are not found on the beaches? Two possible explanations can be offered. The first explanation is that there is a zone of longshore movement at some point between the 7.6 m isobath and the shore. This explanation is considered unlikely for two reasons. Firstly, as noted in section 1.3, wave-induced longshore currents are confined mainly to the breaker zone which is narrow for mixed sand and gravel beaches. Secondly, waves should become increasingly refracted in the shoaling water and therefore should tend to approach more nearly parallel to the coast. There is therefore no mechanism for a zone of longshore movement.

The second explanation, favoured by the author, is that the onshore movement of fine sediments is balanced by an increasing gravitational component as the coast is approached. This was the pattern of movement proposed by Niedoroda and Swift (1981) for nearshore areas. Landward of the point of balance the offshore gravitational component would dominate and fine sediment would move offshore. Longshore transport would occur as a component of the on-offshore transport on occasions when the waves approached the coast at some angle. This proposed pattern of movement is supported by the nearshore profiles shown in figure 3.2. These profiles show increasing gradients in a shoreward direction, even allowing for the steep descent of the beaches. The reason why coarse sediment continued to move landward despite the increased gravitational component is probably due to increased asymmetry in the wave-induced currents in this area.

The currents may exceed the threshold for landward movement under the wave crest but not exceed the threshold for seaward movement under the trough. In these cases the sediment would move only in a landward direction.

The sorting process outlined in the second explanation could be repeated in Caroline Bay but on a much smaller scale. The Bay is sheltered by Timaru Harbour and is exposed to relatively low wave energies. Therefore wave-induced currents within the Bay are capable of moving only relatively fine sediments. These sediments are, however, sorted by the wave-induced currents with the relatively coarser sediment being moved onto the beach. The mean grain size of the beach sediment was 3.18 ϕ, for example, while the mean grain size of the westernmost sample shown in figure 3.6 was 3.44 ϕ. Therefore the proposed sorting process is consistent with the known movement of very fine sand into Caroline Bay. Progradation is occurring in the Bay simply because of the large supply of fine sediments available on the seafloor.

The proposed pattern of sediment movement in a dominantly on-offshore direction is consistent with the sedimentation that occurs in Timaru Harbour entrance channel and the dispersion of dredge spoil dumped to the north of the harbour. The eastern orientation of the channel means that it is substantially exposed to sediment transport by waves approaching from any direction other than east. The wave direction frequency diagrams shown in figure 3.14 indicate that waves approaching from the sector east-north-east to south-south-east can be expected to predominate along the length of the channel and therefore cause substantial sedimentation in the channel. The sand and gravel portion of the dredge spoil dumped 3 km to the north of the harbour and 1.5 km offshore would simply disperse in a landward direction.

The pattern of on-offshore sediment movement proposed for the study area is contrary to the longshore pattern of movement that previous workers have proposed (for example Kirk 1977; Tierney 1977; Kirk 1978; Tierney and Kirk 1978; Gibb and Adams 1982). No evidence presented by these workers contradicts the present interpretation. In fact evidence presented by Kirk (1978) supports the present proposal. From a tracer study Kirk found that sediment transport at a site 3 km to the north-east of the harbour and 2 km offshore was in a vector mean direction of a few degrees south of north-west, that is, landward. Kirk (1978, p. 12) concluded that "sand transport at the tracer site was strongly unidirectional ... but that there were minor components of movement in all other directions."

The rollability study undertaken by Kirk (1977) was interpreted as representing an inshore movement of coarser sand particles and a simultaneous diffusion offshore of the finer sand. These movements were thought to be superimposed on an overall northward regional drift. However, the average relative rollability values also displayed a pattern of "axes" oriented approximately north-east/south-west. These "axes" therefore run approximately parallel to the bottom contours and the coastline, that is, they define a predominant shore-normal gradient. It is suggested here that this is indicative of a general pattern of predominant on-offshore movement rather than of dominant longshore movement. This same pattern is generally repeated in figure 2.9 where the relative rollability values for one of the coarse sand fractions (0.355 mm) and for a very fine sand fraction (0.075 mm) are presented. It is therefore concluded that the general pattern of movement suggested by the rollability analysis does not contradict the proposal that on-offshore transport dominates in the area.

The reasons why previous workers were apparently preoccupied with longshore movement for the study area probably relate to the pressing practical problems of port operation which result from the longshore component of the total sediment transport. Added emphasis was provided by the work of Carter and Heath (1975) who laid great stress on a general northward movement of sediments on the continental shelf of the east coast of the South Island. There has then been a tendency for other workers to accept implicitly a dominance of longshore transport in the nearshore zone (for example Gibb and Adams 1982). However, the processes operating on the beaches, in the nearshore and on the shelf proper are quite different and can therefore result in different transport patterns for these areas. The transport zones calculated in section 3.6.1 using the technique of Hallermeier (1981a,b) support the division of the profile into zones of distinctly different movements.

8.4 NEARSHORE SEDIMENT TRANSPORT THEORIES

Section 1.3 outlined four theories of wave-induced nearshore sediment transport. The theories were proposed by Cornish (1898), Cornaglia in Zenkovich (1967, p. 101), Grant (1943) and Niedoroda and Swift (1981), respectively. These theories are now reviewed in the light of the results from the present study.

Grant (1943) proposed that all bedload sediment transport would be in the direction of wave advance (onshore) because of the asymmetry in the wave-induced currents and because of the mass transport effect. Offshore movement would occur principally through rip currents. Rip currents are unlikely to be important in the study area because of the narrow breaker zone. During experiment 1 periods of offshore movement occurred, contradicting the theory. Also, it was noted in the previous section that fine sediment does not move on to the coarse grained beaches that dominate the study area. For these reasons Grant's theory is considered to be unsatisfactory.

Niedoroda and Swift (1981) also proposed onshore movement of sediment in water depths less than 10 m due to the asymmetry of wave-induced currents. They believed, however, that if equilibrium was to be approached or maintained, at some point the onshore movement would be balanced by an offshore gravitational component. This theory was used in the previous section to explain why all sediment sizes moved a net distance onshore at a site 1.4 km offshore but that only coarse sediments are found on the beaches.

Niedoroda and Swift suggest in their theory that the balance between on-offshore movement would be controlled by slowly varying currents caused by wind-driven upwelling and down-welling. In the study area it is likely that the affect of such currents would be overshadowed by changes in wave conditions. These changes would alter the relationship between the asymmetry in the wave-induced currents and the offshore gravitational component and hence shift the point of balance between the two.

Cornish (1898) outlined a mechanism by which asymmetric wave-induced currents could preferentially move coarse particles onshore. An extended version of Cornish's theory was proposed in section 4.7.4.8 to explain the relationship found between the index of net movement and grain size during experiment 1. The relationship showed that there was an increasing tendency for landward movement with increasing grain size. The proposed extension to the theory stated that with increasing grain size there would be an increasing tendency for landward movement because the threshold for movement would be exceeded more frequently and for longer time periods under the crest than under the trough. Cornish also proposed that while wave asymmetry was moving coarse particles onshore finer particles would move a net distance either way but, if either the bottom sloped seaward or there was a net seaward drift of water, the finer particles would move a net distance seaward. The study area is dominated by wave-induced currents which should produce a net onshore drift of water at the seabed (see section 1.3). A seaward drift of water is therefore unlikely. The importance of bottom slope has already been mentioned and is considered further below.

It is believed that the theories of both Niedoroda and Swift (1981) and Cornish (1898) can be incorporated into a slightly modified version of the null point theory of Cornaglia _in_ Zenkovich (1967, p. 101) which would best explain the observed patterns of movement in the study area. The original theory states that when a particle is seaward of its neutral line it will move seaward because the degree of wave asymmetry is less and, conversely, when a particle is landward of its neutral line it will move onshore because of the increased wave asymmetry. This is only true, however, when the slope, and hence the gravitational component, is constant. In the study area bottom gradients decrease in a seaward direction. It is suggested that if a particle is offshore from its neutral line, both the gravitational component and the asymmetry will be reduced, but that the asymmetry will dominate and the particle will move onshore. Conversely, if a particle is shoreward of its neutral line both the gravitation component and the asymmetry will be increased, but in this case the gravitational component will dominate and the particle will move seaward. If this modification to the theory is made then larger waves would displace the null point shoreward because an increased gravitational component would be required to balance the increased asymmetry in the wave-induced currents.

Both the null point theory and the theory of Cornish (1898) are based on the asymmetry in wave-induced horizontal oscillatory currents. The proposed extension to

Cornish's theory can therefore be incorporated into the null point theory, irrespective of any gravitational influence. The theory of Niedoroda and Swift (1981) suggests that there is a point in the nearshore where onshore wave-induced motion is balanced by an offshore gravitational component. This is simply the null point.

There is obviously a very complex relationship between the wave-induced currents, the offshore gravitational component, and the threshold for sediment movement. Because wave conditions are variable through time the position of the null point for a given size will also change through time. Therefore at any point in the nearshore both onshore and offshore movement could occur at various times. There would, however, be a general trend of movement at each point which would be related to the average wave conditions. This could explain why periods of seaward movement occurred during experiment 1 even though the overall pattern was one of net landward movement.

8.5 APPLIED ASPECTS

Approximate sedimentation rates for Timaru Harbour entrance channel have been calculated from results obtained during the study. The rates were based on the following assumptions:

a) All sediment travelling into the channel is trapped. This assumption may not at first appear to be justified because of the accretion in Caroline Bay. Tierney and Kirk (1978) treated the accreting material as sediment that had bypassed the channel. However, it should be clear from the previous discussion of nearshore sediment transport patterns in the study area (section 8.3.2) that the sediment in Caroline Bay can be derived from the seafloor to the north of the port. This idea is supported by the grain size data for Caroline Bay (section 3.3.4.2) which suggested that sand entered the Bay from the north. The accretion in Caroline Bay therefore does not necessarily imply channel bypassing.

b) The channel is divided into three zones based on water depth immediately to the south of the channel. The innermost zone extends from the Eastern Extension Breakwater to 9.8 m water depth and is 700 m long. The sediment transport rates calculated for this zone are based on the long-term estimates for the 7.6 m water depth. The middle zone extends from 9.8 - 11.1 m water depths and is 1150 m long. The sediment transport rates calculated for this zone are based on the long-term estimates for the 10.0 m water depth. The outermost zone extends from 11.1 m water depth to the seaward end of the channel and is 650 m long. The sediment transport rates calculated for this zone are based on the long-term estimates for the 12.2 m water depths.

c) Sediment transport rates are calculated for very fine sand, fine sand, medium sand and coarse sand because these sizes occurred in seafloor sediment samples taken to the south of the channel. It has been assumed that all of these sizes are available for transport.

d) Sediment transport rates for medium sand for the two innermost zones were assumed to be the same as for the fine sand. The reason for this was that, as stated in section 8.3.1, the long-term rates given in table 8.3 for medium sand for the 7.6 and 10.0 m water depths appear to be too high.

e) The long-term transport rate for coarse sand was assumed to be 0.015 $m^3\ m^{-1}\ day^{-1}$ for the 7.6 and 10.0 m water depths and 0.006 $m^3\ m^{-1}\ day^{-1}$ for the 12.2 m water depth.

f) Wave approach is from the south-east giving an effective channel length of half the actual length. However, it is acknowledged that the channel will receive sediment from both the north and south flanks, depending on the wave direction.

The resulting sedimentation estimates are presented in table 8.4. The total sedimentation rate was 23 295 $m^3\ yr^{-1}$. This is considerably less than the average of 106 300 $m^3\ yr^{-1}$ removed from the channel by maintenance dredging between 1966 and 1976 (Tierney and Kirk 1978). There are a number of possible reasons for this difference. Firstly, sediments finer than very fine sand were not included in the above sedimentation estimates. Secondly, no account was taken of sediment moving around the end of the Eastern Extension Breakwater from South Beach or of the much higher sediment transport rates that would occur very close to the shore. Both of these factors would increase channel sedimentation at the inner end. Finally, a portion of the 106 300 $m^3\ yr^{-1}$ channel sedimentation may have been derived from collapse of the channel side walls and/or from capital dredging.

TABLE 8.4 CHANNEL SEDIMENTATION ESTIMATES.

SIZE CLASS	SEDIMENTATION RATE (m^3 yr^{-1})			
	CHANNEL ZONE			TOTAL
	<9.8 m Water Depth	9.8-11.1 m Water Depth	>11.1 m Water Depth	
Very Fine Sand	3577	3148	949	7674
Fine Sand	2171	2099	593	4863
Medium Sand	2171	2099	712	4982
Coarse Sand	1916	3148	712	5776
TOTAL	9835	10494	2966	23295

Differential sedimentation rates along the length of the channel would not only be due to varying sediment transport rates across the inshore seabed but would also be affected by changes in the relative depth of the channel. The relative depth (channel depth/water depth) is greatest at the inner end and decreases in a seaward direction. This is the same pattern followed by the sediment transport rates. The inner end of the channel is therefore particularly vulnerable to sedimentation.

Sediment dredged from the entrance channel is currently dumped on the seafloor 3 km to the north of the port and 1.5 km offshore. The fraction of this material coarser than 0.0625 mm median diameter should disperse in a landward direction. It is not known what will happen to the finer sediments but it is likely that any material that does not remain in suspension will be moved offshore.

Experiment 3 showed that coarse sediment could travel from the seafloor to the foreshore of a mixed sand and gravel beach and therefore that such beaches can receive nourishment from the seafloor, provided coarse sediment is available. The dumped dredge sediment could provide a source of such material. The long-term sediment transport rate for granules for the 7.6 m water depth was used to estimate the quantity of granules that could potentially be delivered to a 1 km length of beach. The resulting amount was 5110 m^3 yr^{-1}. However, the long-term average grain velocity for the 7.6 m water depth was 0.19 m day^{-1}. Assuming this value holds for the present dump ground, 1.5 km offshore, and that it is representative of the area from the dump ground to the coast, it would take approximately 22 years for the dumped granules to reach the coast. The actual value will be less than this because the velocity would increase in shallower water. Therefore, there is potential for significant quantities of dredged material to be moved to the beaches although there will be some delay between dumping and nourishment. The nourishment potential could be increased by dumping the dredged sediments as close to the beach as possible. This would both shorten the transport route onshore and subject the dumped materials to higher initial transport rates.

8.6 CONCLUSION

The artificial tracer technique can be successfully applied in the nearshore to provide data on the rates and directions of sediment transport. The technique has two major advantages over the other techniques outlined in section 1.4. Firstly, it enables nearshore sediment transport to be measured directly and, secondly, it is the only technique that enables the differential transport or sorting of a range of sediment sizes or specific gravities to be studied. Such sorting processes are extremely important with respect to beach formation. The artificial tracer technique therefore has a significant role to play in the study of nearshore sediment transport.

The results from the present study were used to calculate long-term sediment transport rates and to determine the patterns of nearshore sediment transport in the study area. It was noted that the processes operating in the nearshore, and hence sediment transport patterns, were quite different to those operating on the beaches or on the continental shelf proper. These processes and patterns are not well understood and require considerable further study. This state of affairs is echoed in the theories of wave-induced nearshore sediment transport which, for the study area anyway, required modification or expansion to adequately describe both the observed local patterns of sediment movement and the broader scale patterns proposed from the experiments.

CHAPTER IX

CONCLUSIONS

9.1 SUMMARY OF MAJOR FINDINGS

The major findings of this study fall into six general areas. These are the nearshore environment and sediment transport potential, sediment transport rates and directions, sediment transport patterns, theories of wave-induced nearshore sediment transport, applied aspects and the application of the artificial tracer technique in the nearshore. The findings in each of these areas are presented below, and where appropriate, broader implications are examined.

9.1.1 The Nearshore Environment And Sediment Transport Potential

1. The gradient of the seafloor in the study area decreases in a seaward direction. This is an elementary observation with important consequences for the transport of sediment.

2. Previous studies at Timaru showed that littoral transport was divided into two separate systems. Coarser sediment is confined to the nearshore face and landward while finer sediment is confined to the seafloor. The separation

of littoral transport into two separate systems and the behaviour of each presents quite a different situation to that commonly found in the literature for sand beach systems.

3. The seafloor in the study area is mantled with a uniform layer of very fine sand. To the north of Timaru Harbour there are two areas which contain gravel while to the south of the harbour there is an area where silt forms a subsidiary fraction to the very fine sand. The finer sediment in the south may be a reflection on the greater water depth in that area. In Caroline Bay grain size patterns suggest that sand is entering the Bay from the north and is sweeping around the Bay in an anti-clockwise direction.

4. Attempts to measure the depth of disturbance of sediment were generally unsuccessful but at one site a depth of disturbance of 0.11 m was measured over a period of 1 month.

5. Some evidence from the bathymetry of the study area and the change in seabed elevation at a site off South Beach suggested that large scale bedforms may be present. Some sediment transport may occur through the migration of these bedforms. No further evidence on the possible role of large scale bedforms in nearshore sediment transport was obtained during the study.

6. An average significant wave height ($\overline{H}_s$) of 0.97 m and an average significant wave period ($\overline{T}_s$) of 10 s were obtained for the period 7 October 1981 to 12 October 1982 from 3728 10 minute wave records obtained at a site approximately 2.5 km offshore.

7. Using the technique of Hallermeier (1981a,b) it was suggested that the study area is characterised by intense sediment transport out to the 7 m isobath and that the remaining area is subject to significant sand transport.

8. Wave-induced oscillatory currents at the 7 m isobath were calculated using the full set of wave data. The average maximum linear current was 51 cm s^{-1}. Using Stokes' second order wave theory it was found that on average the crest velocity exceeded the trough velocity by 20 cm s^{-1}.

9. Wave-induced oscillatory currents are much more important for sediment transport than any other current in the study area. The average maximum linear current is five times the tidal current at the 7 m isobath and even the average difference between the crest and trough velocities is twice the magnitude of the tidal current. Coastal currents are assumed to be negligible and direct wind currents and density currents are thought to be very much smaller than the wave-induced oscillatory currents.

10. At the 7 m isobath the calculated wave-induced oscillatory currents exceeded calculated thresholds for sediment movement for greater than 80% of the time for very fine sand, fine sand, medium sand and coarse sand, 56% of the time for very coarse sand, 28% of the time for granules and 6% of the time for pebbles. Combined with a measured depth of disturbance of 0.11 m there is therefore considerable potential for sediment transport at the 7 m isobath. Sediment transport would be expected to increase shoreward and decrease seaward of this line.

11. The predominant wave direction is from the east to south-east quadrant and sediment transport should therefore be predominantly north-west and shoreward. The tendency for shoreward transport will be enhanced by wave refraction, with this effect increasing in shoaling water.

9.1.2 Sediment Transport Rates and Directions

1. Experiment 1 was located at a site 2 km to the north of Timaru Harbour and 1.4 km offshore, in a water depth averaging 7.6 m. Over a period of 2.3 months fluorescent tracer ranging in size from 0.063 - 19.050 mm median diameter moved a net distance landward. There was an increasing tendency for landward movement with increasing grain size. For the final three sample runs, when mixing of the tracer into the mobile layer was assumed to be complete, the numerical mean sediment transport rate ranged from 0.008 m^3 m^{-1} day^{-1} for granules to 0.028 m^3 m^{-1} day^{-1} for medium sand. Some statistically significant linear relationships were found both between the average grain velocities and wave or wave-dependent parameters, and between the sediment transport rates and wave or wave-dependent parameters. These relationships were all positive and indicate that an increase in the wave or wave-dependent parameters will cause a proportionate increase in the average grain velocity and the sediment transport rate.

2. Experiment 2 was located at a site immediately to the south of Timaru Harbour entrance channel and approximately 2 km offshore, in a water depth averaging 12.2 m. Over a period of 21 days fluorescent very fine tracer sand

moved a net distance both landward and northward at rates ranging from 0.010 - 0.113 $m^3\ m^{-1}\ day^{-1}$. The highest rate is thought to represent the period before the tracer had become fully mixed into the mobile layer.

3. Relationships that had been found between sediment transport rates and wave or wave-dependent parameters, and between average grain velocities and wave or wave-dependent parameters, were used to calculate long-term sediment transport rates for 7.6, 10.0 and 12.2 m water depths using the full set of wave data. Where the relationship involved average grain velocity a long-term thickness of the mobile layer was estimated so that sediment transport rates could be calculated. There were no relationships for coarse sand and so a long-term sediment transport rate could not be calculated for this size class. The rate calculated for medium sand appeared to be too high and was not considered to be representative of actual long-term rates. Leaving out these size classes the long-term rates ranged from 0.014 $m^3\ m^{-1}\ day^{-1}$ (granules) to 0.028 $m^3\ m^{-1}\ day^{-1}$ (very fine and very coarse sand) for the 7.6 m water depth, 0.009 $m^3\ m^{-1}\ day^{-1}$ (granules) to 0.016 $m^3\ m^{-1}\ day^{-1}$ (very coarse sand) for the 10 m water depth and 0.005 $m^3\ m^{-1}\ day^{-1}$ (fine sand) to 0.008 (very fine and very coarse sand) for the 12.2 m water depth. The calculated rates are considered to be order of magnitude estimates only. The rate of 0.028 $m^3\ m^{-1}\ day^{-1}$ calculated for very fine sand for the 7.6 m water depth is very much lower than the rate of 0.46 $m^3\ m^{-1}\ day^{-1}$ calculated by Kirk (1978) for very fine sand in 8 m of water.

9.1.3 Sediment Transport Patterns

1. Results from experiments 1 and 2 indicated that there was a wave-induced net landward movement of all grain sizes tested. Results from experiment 3 showed that waves with an average significant height slightly greater than 1 m and an average period ranging from 9 - 11 s are capable of moving pebbles up to 28.4 mm median diameter from the seafloor to to the foreshore of a mixed sand and gravel beach. It would therefore appear that coarse sediments moving landward on the seafloor will eventually move up on to the beaches. The finer sediments, however, are not found on the beaches. It was proposed that the onshore movement of fine sediments is balanced by an increasing offshore gravitational component as the coast is approached. This was the pattern of movement suggested by Niedoroda and Swift (1981) for nearshore areas. Under these conditions nearshore transport is dominated by on-offshore transport and longshore movement occurs only as a component of the on-offshore movement on occasions when waves approach the coast at some angle. It is thought that the same pattern of movement is repeated on a smaller scale in Caroline Bay. The proposed pattern of predominant on-offshore movement is contrary to the pattern of dominant longshore movement suggested for the area by other workers. However, no evidence presented by these workers contradicts the present interpretation.

2. The gradient of the nearshore seafloor has a significant influence on wave-induced sediment transport in

this area. Any successful model of wave-induced nearshore sediment transport must therefore incorporate the effect of seafloor gradient.

3. The processes operating on the beaches, in the nearshore and on the shelf proper are quite different and can therefore result in different transport patterns for these areas. Consequently, it is not possible to have a single sediment transport rate representing movement over the entire area.

4. Results from experiment 3 have shown that the mixed sand and gravel beaches in the study area could receive a supply of sediment from the seafloor. The rate of supply is probably small, especially relative to other components in the sediment budget such as longshore transport in and landward of the surf zone.

9.1.4 Theories Of Wave-Induced Nearshore Sediment Transport

1. Results from experiment 1 showed that there was an increasing tendency for landward movement with increasing grain size. This can be explained by extending the theory of Cornish (1898) by stating that with increasing grain size there will be an increasing tendency for landward movement because the threshold for movement will be exceeded more frequently and for longer time periods under the crest than under the trough.

2. The theory of Niedoroda and Swift (1981) states that wave asymmetry will cause an onshore movement of sediment but that if equilibrium was to be approached or

maintained at some point on the profile this onshore movement would be balanced by an offshore gravitational component. Niedoroda and Swift suggest that an on-offshore movement would then be controlled by slowly varying currents caused by wind-driven upwelling and downwelling. In the study area it was thought that the likely effect of such currents would be overshadowed by changing wave conditions. These changes would shift the point of balance between the asymmetry and the gravitational component which could result in the direction of movement being reversed on some sections of the profile.

3. It is believed that the theories of Cornish (1898) and Niedoroda and Swift (1981) can be incorporated into a slightly modified version of the null point theory of Cornaglia in Zenkovich (1967, p. 101) which would best explain the observed patterns of movement in the study area. In the original theory the bottom gradient was assumed to be constant. In the study area, however, the gradient of the seafloor decreases in a seaward direction. Taking this into consideration it is proposed that if a particle is offshore from its neutral line, both the wave asymmetry and the gravitation component will be reduced, but the asymmetry will dominate and the particle will move shoreward. Conversely, if a particle is shoreward from its neutral line both the gravitational component and the asymmetry will be increased, but the gravitational component will dominate and the particle will move seaward. Because the null point theory is based on wave asymmetry it can incorporate the proposed extension to the theory of Cornish (1898). The

theory of Niedoroda and Swift (1981) involves a point of balance between wave asymmetry and an offshore gravitational component. This is simply the null point.

4. There is obviously a complex relationship between the wave-induced currents, the offshore gravitational component and the threshold for sediment movement. Changes in wave conditions will alter the null point position. Therefore, at any point on the nearshore seafloor both onshore and offshore movement can potentially occur but there should be a general trend of movement at each point which will be related to the average wave conditions.

9.1.5 Applied Aspects

1. Timaru Harbour entrance channel can receive sedimentation from both its north and south flanks. Based on the long-term sediment transport rates and a number of assumptions channel sedimentation was estimated at 23 295 m^3 yr^{-1}. This is much lower than the average of 106 300 m^3 yr^{-1} removed from the channel by maintenance dredging between 1966 and 1976. Possible reasons for the difference include the following. Firstly, sediments finer than very fine sand were not included in the estimate; secondly, no account was taken of sediment moving around the end of the Eastern Extension Breakwater or of the much higher sediment transport rates that would occur close to the shore; and, thirdly, a portion of the 106 300 m^3 yr^{-1} channel sedimentation may have been derived from collapse of the channel side walls and/or from capital dredging.

2. The sand and gravel portion of the dredged sediment which is dumped on the seafloor 3 km to the north of the port and 1.5 km offshore should disperse in a landward direction. The coarse sediment could provide some nourishment to the mixed sand and gravel beaches in the area, although it would take some years for the dumped material to travel to the beach.

9.1.6 Application Of The Artificial Tracer Technique In The Nearshore

1. For studies of fine nearshore sands in New Zealand fluorescent tracer is considered to be the best tracer type. A magnetic tracer, ironsand, was tried in a field experiment but it lacked sufficient sensitivity to provide useful results. A chemical tracer, Eu labelled sand, was also tried. Laboratory tests showed that the Eu labelled sand could be used as a sediment tracer using atomic emission for detection. A field experiment, however, showed that it lacked sufficient sensitivity. If either the ironsand or the Eu labelled sand were to be used for future experiments the sensitivity would have to be increased.

2. For coarse sediments in situ detection would be a definate advantage. This could be achieved by using either radioactive or aluminium pebbles.

3. For tracer studies involving sample collection a rope grid placed on the seafloor can enable fast, precise position fixing during a sampling operation undertaken by divers. For fine sediment an alternative position fixing

method may be required to sample the area surrounding the grid.

4. There are a number of advantages to be gained by using divers for sediment tracing studies and it is recommended that they be employed wherever possible.

5. Diver operated sample tubes with pistons enabled most grid samples to be retained intact. Further improvement would be attained if clear plastic core tubes were used.

6. In areas subjected to relatively strong current action it is recommended that at least 5 days be allowed for complete mixing of the tracer into the mobile layer.

7. Two assumptions must be made when using the spatial integration method to determine sediment transport rates and directions. Firstly it must be assumed that sediment transport is more or less uniform over the study area and, secondly, it must be assumed that tracer behaviour is independent of the manner in which it was introduced. Both of these assumptions can be satisfied in the nearshore. A further requirement is that all tracer grains released can be accounted for. The significance of this requirement is unknown and research is required to establish a standard accounting procedure and then to determine the minimum percentage of tracer that must be accounted for, using this technique, for the results to be significant.

8. The artificial tracing technique can be used to obtain estimates of nearshore sediment transport rates and directions.

9.2 STUDY EVALUATION AND SUGGESTIONS FOR FUTURE RESEARCH

The broad objectives of this study were listed in chapter 1. The first was to obtain direct measurements of both the rates and directions of nearshore sediment transport at Timaru using artificial tracers. A number of sediment transport measurements were obtained during this study by using fluorescent tracers. These measurements were, however, made at two sites only. At one of the sites a range of sediment sizes was studied while at the other site only one sediment size was studied.

The second broad objective was to find relationships between the measured sediment transport rates and wave or wave-dependent parameters so that long-term sediment transport rates could be determined from wave records. Some relationships were found during the study, but not many could be used directly to estimate long-term sediment transport rates from wave records. One problem with all of the relationships was a lack of data. This made it difficult to place much confidence in either the relationships or in the long-term sediment transport rates that were calculated. The study was therefore only partially successful in realising the first two broad objectives. A greater degree of success would have been achieved if more seafloor sediment tracing experiments had been undertaken.

The third broad objective of this study was to investigate the practical application of artificial tracing techniques in the study of nearshore sediment transport.

This was achieved reasonably successfully during the study. A number of improvements in the practical application of the technique were made during the study and further improvements were suggested for future experiments. The study was not, however, particularly successful in finding an alternative to fluorescent tracer for use in tracing fine nearshore sediments in New Zealand. Eu labelled sand would provide an alternative provided the sensitivity could be improved in some way. Further laboratory tests are required to determine if a higher Eu concentration can be attained during the labelling process.

A pattern of sediment transport was proposed for the study area. It was suggested that the net onshore transport of fine sediments that was indicated during experiments 1 and 2 would be balanced by an increased offshore gravitational component at some point between the experiment sites and the coast. Further studies are required to confirm this pattern of movement. Such studies could employ artificial tracers to follow the movement of a range of sediment sizes at a number of sites running perpendicular to the coast. Information gained from such experiments could lead to a better understanding of nearshore sediment transport and could enable existing nearshore sediment transport theories to be tested or new ones to be formulated.

Some evidence was found during this study to suggest that some of the nearshore sediment transport may occur through the migration of large scale bedforms. Further studies are required to investigate the role of such bedforms in nearshore sediment transport. In addition, the presence of small scale bedforms was noted during this study but their influence on sediment transport in the study area is unknown and requires investigation.

Finally, this study has been concerned only with bedload transport in the nearshore. Some of the sediments studied may, however, also be transported in suspension at times. Further research is required to determine the suspended sediment load and to determine the proportions of the total load that travels in suspension under different conditions.

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APPENDIX I

GRAIN SIZE PARAMETERS

FROM FOLK (1974)

1. GRAPHIC MEAN

$$M_z = (\phi 16 + \phi 50 + \phi 84) / 3$$

2. INCLUSIVE GRAPHIC STANDARD DEVIATION (SORTING)

$$\sigma_I = (\phi 84 - \phi 16) / 4 + (\phi 95 - \phi 5) / 6.6$$

Verbal Classification

< 0.35 φ	very well sorted
0.35 to 0.50 φ	well sorted
0.50 to 0.71 φ	moderately well sorted
0.71 to 1.00 φ	moderately sorted
1.00 to 2.00 φ	poorly sorted
2.00 to 4.00 φ	very poorly sorted
> 4.00 φ	extremely poorly sorted

3. INCLUSIVE GRAPHIC SKEWNESS

$$Sk_I = (\phi 16 + \phi 84 - 2\phi 50) / 2(\phi 84 - \phi 16)$$

$$+ (\phi 5 + \phi 95 - 2\phi 50) / 2(\phi 95 - \phi 5)$$

Verbal Classification

+1.00 to +0.30	strongly fine-skewed
+0.30 to +0.10	fine-skewed
+0.10 to -0.10	near-symmetrical
-0.10 to -0.30	coarse-skewed
-0.30 to -1.00	strongly coarse-skewed

APPENDIX II

WAVE-INDUCED OSCILLATORY CURRENT EQUATIONS

FROM U.S. COASTAL ENGINEERING RESEARCH CENTER (1977)

1. LINEAR (AIRY) WAVE THEORY

$U_{max} = (HgT/2L \; 1/\cosh(2\pi d/L) \; \cos\theta) \; 30.48$

2. STOKES' SECOND ORDER WAVE THEORY

$U_{max} = (HgT/2L \; 1/\cosh(2\pi d/L) \; \cos\theta$

$+ \; 3/4 \; (\pi H/L)^2 \; C \; 1/\sinh^4(2\pi d/L) \; \cos 2\theta) \; 30.48$

where U_{max} = maximum wave-induced horizontal current velocity at the seabed (cm s^{-1})

- H = wave height (ft)
- g = gravitational acceleration (ft s^{-2})
- T = wave period (s)
- L = wavelength (ft)
- d = water depth (ft)
- π = 3.14159
- θ = phase angle a) under a crest $\theta = 0$; b) under a trough $\theta = \pi$
- C = wave celerity = $gT/2\pi \; \tanh(2\pi d/L)$