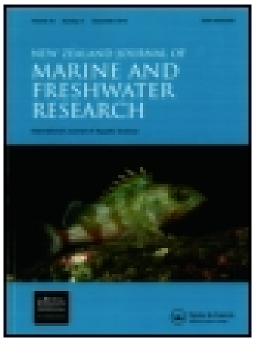

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Stability of an artificially nourished beach, Balaena Bay, Wellington Harbour, New Zealand

LIONEL CARTER
JOHN S. MITCHELL
New Zealand Oceanographic Institute
Division of Marine and Freshwater Science
Department of Scientific and Industrial Research
P. O. Box 12-346, Wellington
New Zealand

Abstract Balaena Bay, Wellington Harbour, New Zealand, has a small pocket beach that was covered originally by pebbles and cobbles. In February and October 1982, the beach was nourished with sandy granular gravel, the stability of which was monitored until February 1984. Although isolated from oceanic swell, the new beach readily responded to locally generated wind waves which induced both northwards and southwards longshore drift. The net effect was erosion of the southern beach, aggradation over the central beach, and minor fluctuations at the northern end. Yet despite this mobility nearly all the nourishment sediment was retained in the littoral zone. Beach volumes, calculated for each survey, varied little and sediment distribution patterns revealed negligable transport of nourishment sediment to adjacent beaches and offshore areas. Stability is further confirmed by compositional data which record no preferential loss of the sandstone, argillite, and quartz components. The only compositional changes were the incorporation into the new beach of small (< 10%) quantities of sediment derived from the old beach surface and from biogenic productivity.

Keywords beach stability; nourishment; sediment transport; coastal morphology; beach gravel; sediment composition; wind waves; pocket beach; Balaena Bay; Wellington Harbour

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INTRODUCTION

Wellington has few sandy beaches within easy reach of the city. Port development, construction of coastal roads, and a poor supply of natural sand have relegated inner harbour beaches to small pockets of gravelly sediment. Oriental Bay, the closest beach to the city, was originally covered by gravel but was artificially sanded in 1944 to produce what is now a popular, recreational facility (Lewis et al. 1981). In 1982 the decision was made to nourish Balaena Bay beach — a cobble and pebble-strewn pocket beach situated just 2.7 km from Oriental Bay (Fig. 1, 2).

The key problem facing the nourishment programme, and the problem to which this paper is addressed, concerns the stability of the new, sandy gravel beach bordering Balaena Bay (Fig. 2). Studies of the stability of such coarse-grained beaches deal mainly with sites exposed to ocean swell (e.g., McLean & Kirk 1969; Matthews 1980; Dingler 1981). There is little relevant information for beaches in semi-protected environments which could be used to assess rates of erosion/deposition or onshore/offshore/longshore transport. Data from nearby Oriental Bay (Lewis et al. 1981) could not be applied with confidence because of marked differences in the wave climates and nourishment materials.

Similarly, a theoretical assessment of beach stability (e.g., James 1975; US Army 1977), was also of little value. Such an assessment assumes that the grain size distribution of the original beach sediment is a reflection of the energetics of the beach system and, therefore, by comparing this size to that of nourishment sediment, some estimate of the latter's stability is derived. However, in the situation of Balaena beach the coarse gravel does not indicate a high energy environment incapable of retaining sand. Rather, the paucity of sand is a consequence of a low natural supply (e.g., Lewis & Carter 1976). The abundance of cobbles and pebbles is primarily the result of road construction; these materials originating from the road fill.

The favoured approach to the problem was to monitor changes in beach morphology and sediments over a minimum period of an annual seasonal cycle beginning from the onset of beach

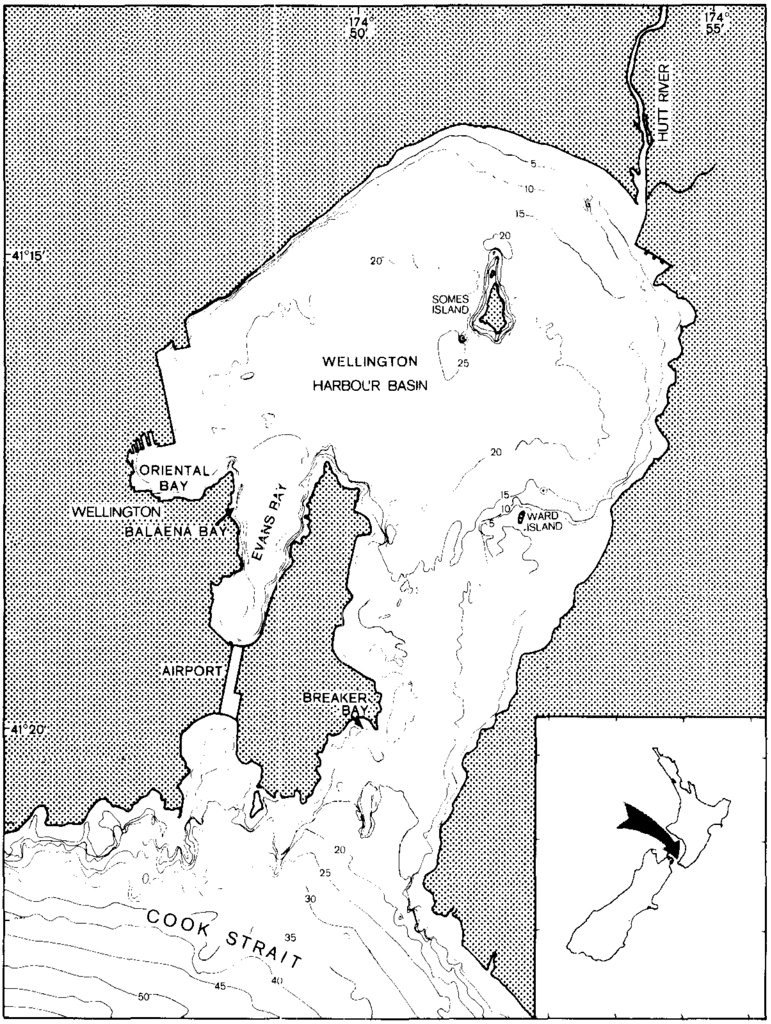


Fig. 1 Location chart for Balaena Bay and Wellington Harbour. Metric bathymetry is from Herzer (1976).

nourishment. The resultant data should serve to guide future nourishment programmes not only for Balaena beach, but for similar littoral environments.

Sampling and analysis

The beach was nourished on two occasions with sandy granular gravel transported by truck from Breaker Bay beach at the entrance to Wellington Harbour (Fig. 1):

1. During the first two weeks of February 1982, the northern beach between the changing sheds and reclamation, received c. 250 m³ of sediment which was spread over that part of the beach by a front-end loader.
2. On October 10, 1982 a further c. 250 m³ of sediment was dumped and spread but this time over both the northern and southern sectors of the beach.

After the first nourishment phase, shore-normal transects were established in order to measure the beach profile and thickness of nourishment sediment (Fig. 2). The latter task was accomplished by digging down to the readily-identifiable old beach surface at 3–11 sites along each transect. Surficial sediment samples were also collected to determine alongshore and offshore sediment movement at different wave energy levels corresponding to high, middle, low, and sub-tide (Fig. 2). Profiling and sampling were repeated at 1–2 month intervals until completion of the annual programme in February 1983. A final survey was made one year later to assess any net annual change. All surveys were accompanied by the photographic recording of beach morphology. In addition, the southern boundary of the nourishment zone after the first

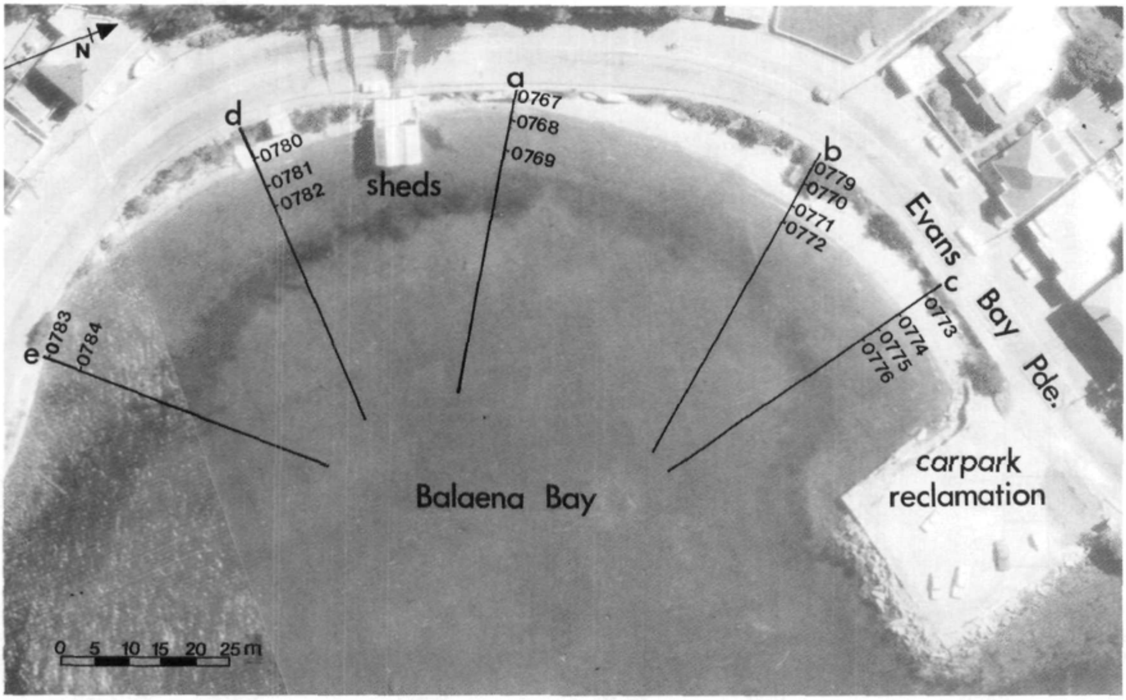


Fig. 2 Aerial view of Balaena beach with location of Profiles a, b, c plus Stations O767–O776 (occupied February 1982–February 1984) and Profiles e, d plus Stations O780–O784 (occupied October 1982-February 1984).

dumping was mapped at various times to help evaluate short-term sediment movements under varying wave conditions.

Sediments were routinely sieved into 0.25 ϕ fractions and the resultant textural parameters computed according to Folk (1965). A suite of representative samples were also analysed for $CaCO_3$ by acid titrimetry to determine the biogenic component of the beach sediment. The mineralogy of samples was identified as a means of ascertaining any interchange between the beach and bay, and between the new and the original beaches.

Physiographic setting

Balaena Bay is a small semi-circular indentation, 150 m across its mouth. It opens eastward into the much larger Evans Bay, a north-south aligned corridor which is flanked by prominent ridges (Fig. 1). The northern headland of Balaena Bay is a small reclamation and the southern limit is marked by a low relief, rocky promontory that is largely submerged at high tide.

The beach itself is 160 m long and is bordered by the coastal road, Evans Bay Parade. Thus, the backdrop is entirely artificial consisting of 1–2 m high concrete walls, boulder revetments, crib walls, and sections of partially exposed road fill. Beach width is variable reaching a low tide maximum of c. 20 m near Profile b (Fig. 2).

Seaward of the beach, the featureless bay floor gently descends to the 6 m isobath, about 200 m from shore (Lewis & Carter 1976). Here the seafloor markedly steepens at the sides of a 20 m-deep trough which occupies most of Evans Bay.

HYDRAULIC REGIME

The fate of a beach is ultimately determined by the hydraulic regime of tides, meteorologically forced currents, and waves. In Balaena Bay, the tides are semi-diurnal with a range of 1.0 m at mean spring tides and 0.95 m at mean neap tides (Marine Division 1983). The accompanying tidal flow is slow, e.g., in nearby Lambton Harbour, the flow 1 m above the seafloor is less than 0.015 m s^{-1} (Heath 1977).

Evans Bay is completely protected from deep ocean swell, thus waves are driven entirely by local winds. In the absence of diagnostic wave records,

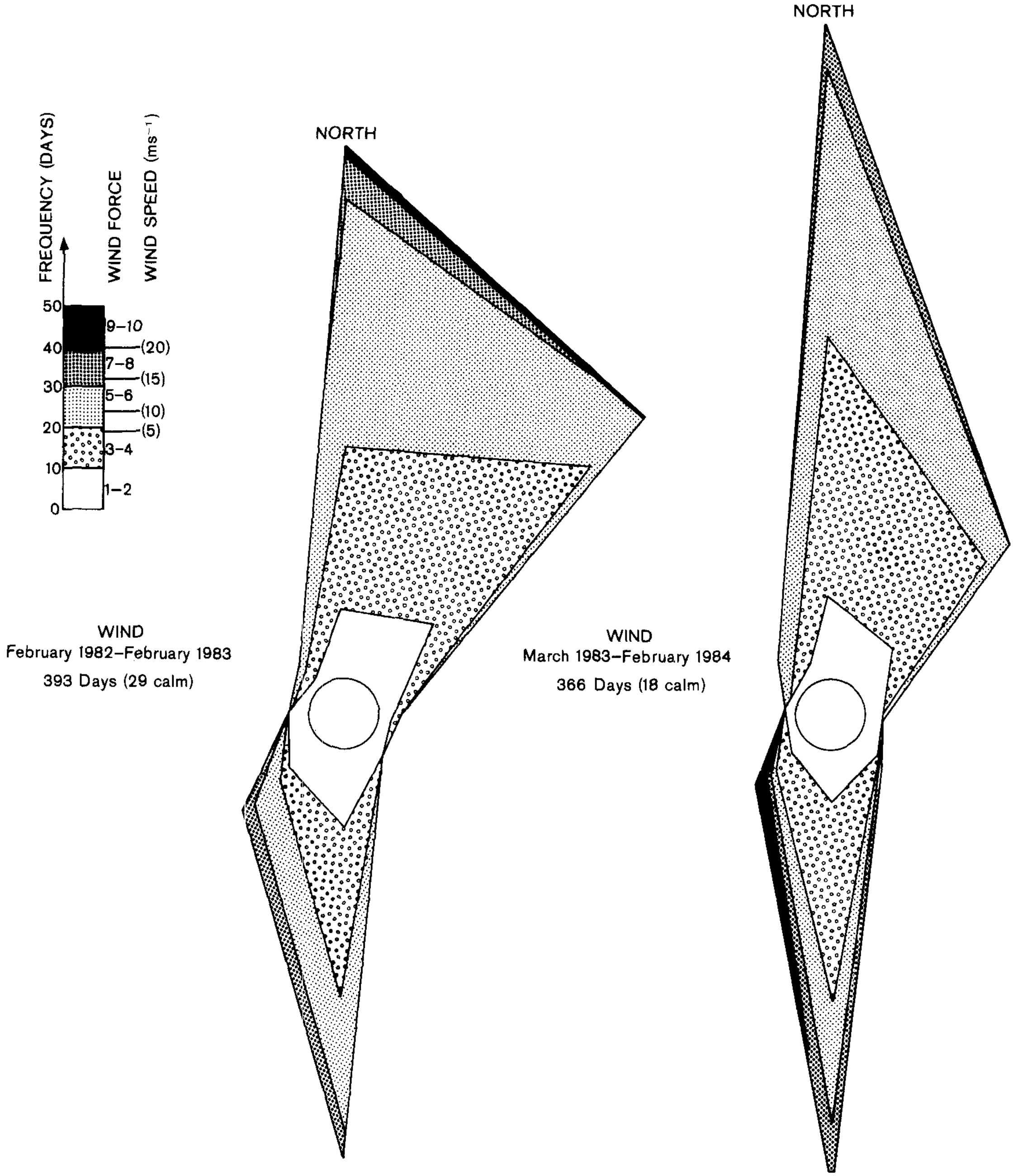


Fig. 3 Wind climate summarised from New Zealand Meteorological Service (1982–84) records. Note the strong north-easterly component of the 1982–83 record.

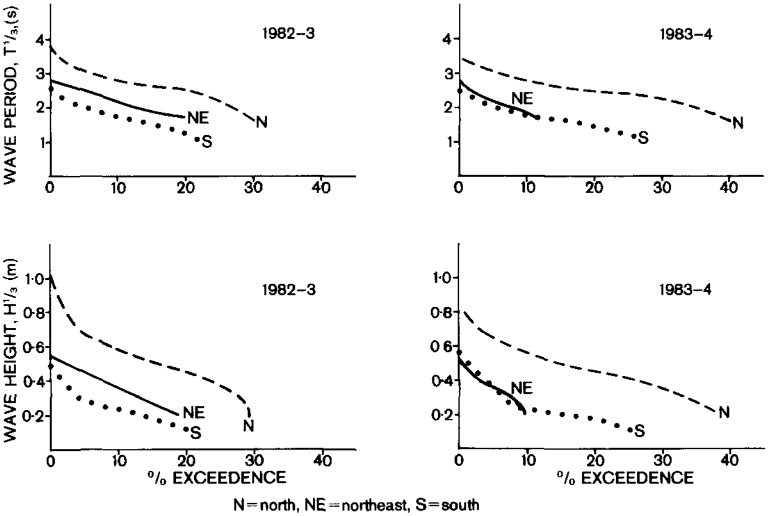


Fig. 4 Exceedence curves for significant wave height (H⅓, m) and period; (P⅓, s) hindcast from wind velocity records using US Army (1977) hindcast curves for waves generated by winds $\geq$ Force 3 ($\geq$ 3.4 m s^{-1}).

the local wave climate for February 1982 to February 1984 has been hindcast (US Army 1977) using wind velocity records taken at Wellington Airport (Fig. 3).

Waves approaching Balaena Bay are driven from the north, north-east, and south (Fig. 4). Of these, northerly waves are the most frequent and largest with significant heights (H⅓) = 1.1 m and significant periods (T⅓) = 3.8 s. The next most frequent direction of approach is from the north-east where maximum waves of H⅓ = 0.6 m and T⅓ = 2.8 s are generated. Maximum waves driven from the south are usually the smallest of the main wave fields (H⅓ = 0.5 m; T⅓ = 2.5 s) reflecting the short effective fetch of only 1 km.

Evaluation of the hindcast wave climate shows that compared to 1983-84, 1982-83 was a period of more intense wave activity particularly from the north-east (Fig. 4). This direction is significant for the beach because it is the only direction of direct wave attack, affecting primarily the southern beach. By comparison, waves from the south and north are refracted around headlands and approach the beach at a high angle that diminishes as the waves travel along the beach face (Fig. 5). From the oblique angle of wave approach, the resultant longshore currents travel north under southerly wave attack and the reverse direction in northerly conditions. In addition, localised northerly wave effects were noted at both ends of the beach. At the northern end, the beach is protected from refracted waves by the reclamation, but is subjected to diffracted and reflected waves. At the southern end a combination of shoreline curvature and an impermeable sea wall serve to reflect northerly waves back along the beach to the north, thereby reversing the southward longshore drift typical of northerly wave attack.

BEACH CHANGES 1982-84

Morphology

The original beach exhibited a simple profile consisting of a 3-7 m wide berm and a 17-20 m wide face, inclined seaward at 7-8°. In contrast, the new beach, one week after the dumping and spreading of the nourishment material, was devoid of a berm and the beach face was reduced to 6°. However, this artificial profile was short-lived. One month later a berm had re-established and the beach face inclination returned to 7-8°. As with the original beach, no longshore bar system was recorded seaward of the beach face. The basic profile remained for the rest of the survey period except for an occasional development of a secondary berm, seaward of the main berm and a temporary masking of morphology by the dumping and spreading during the second nourishment phase (Fig. 6).

Throughout the survey, the beach underwent a number of changes that are most graphically revealed in a time-series sequence of isopachs drawn for the new sediment cover (Fig. 7).

Under southerly wave attack, the prevalent conditions during the autumn and winter of 1982, the beach moved northwards and shorewards. The main depocentre was in the vicinity of Profile b where the beach surface rose an average of 0.1 m (Fig. 7). The gain was matched by losses in the sediment cover to the south (Profile a) where the

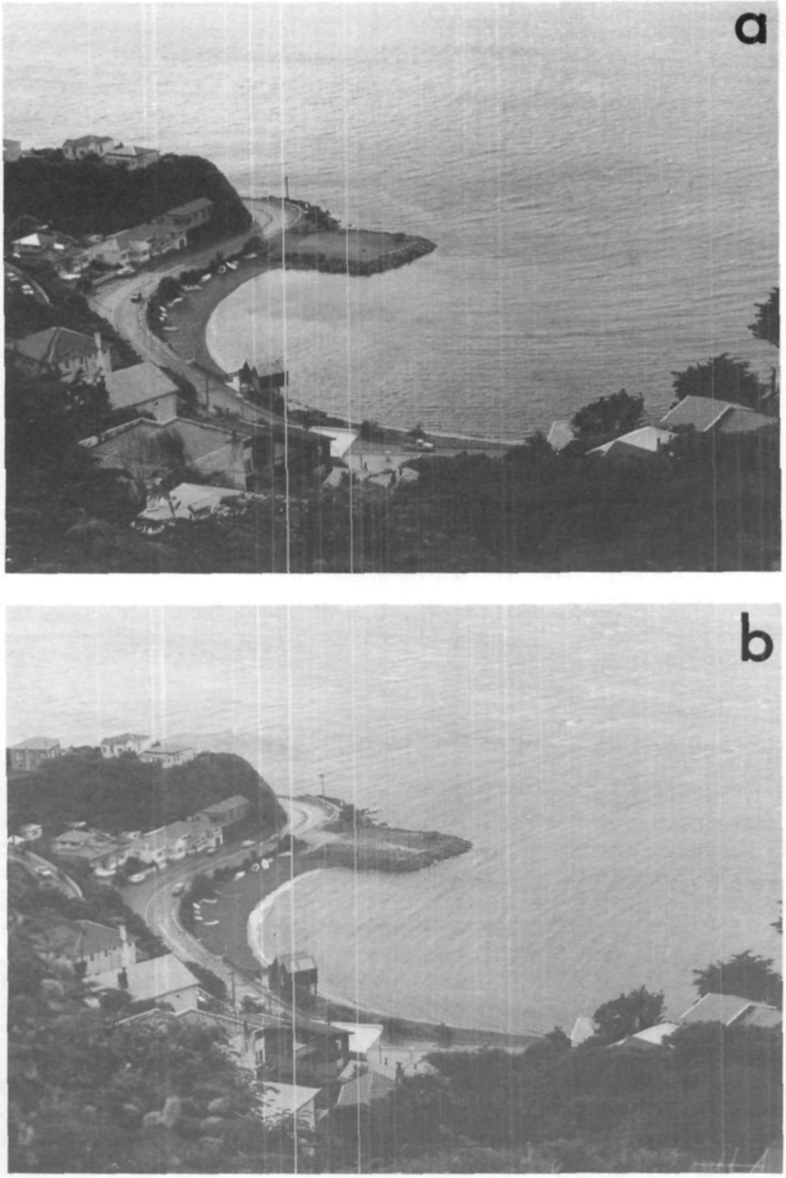


Fig. 5 High angle, oblique photographs displaying wave refraction and angle of wave approach at the beach face under **a**, northerly and **b**, southerly winds.

old beach surface was exhumed (Fig. 8). This trend reversed in the spring of 1982 when, at a time of prevailing northerly waves, sediment began to move southwards (Fig. 7f, g). However, intervention by occasional southerly gales tended to render this process episodic.

After the second nourishment, in the summer of 1982–83, Balaena beach reached its maximum thickness of 0.46 m, again at Profile b. Over the next three months, this sediment was distributed more or less evenly to the south, except at the southern tip of the beach where a reversal in drift was recorded. This reversal became more apparent a year later when the northward drift was noted as far as the changing sheds (Fig. 7h–j).

In addition to these major changes, a series of small-scale changes were detected at the limit of the first nourishment zone, near the changing sheds. Here, the fresh, grey nourishment sediment formed a sharp boundary with the iron-stained pebble-cobble surface of the underlying old beach, and thus provided favourable conditions for sediment tracer

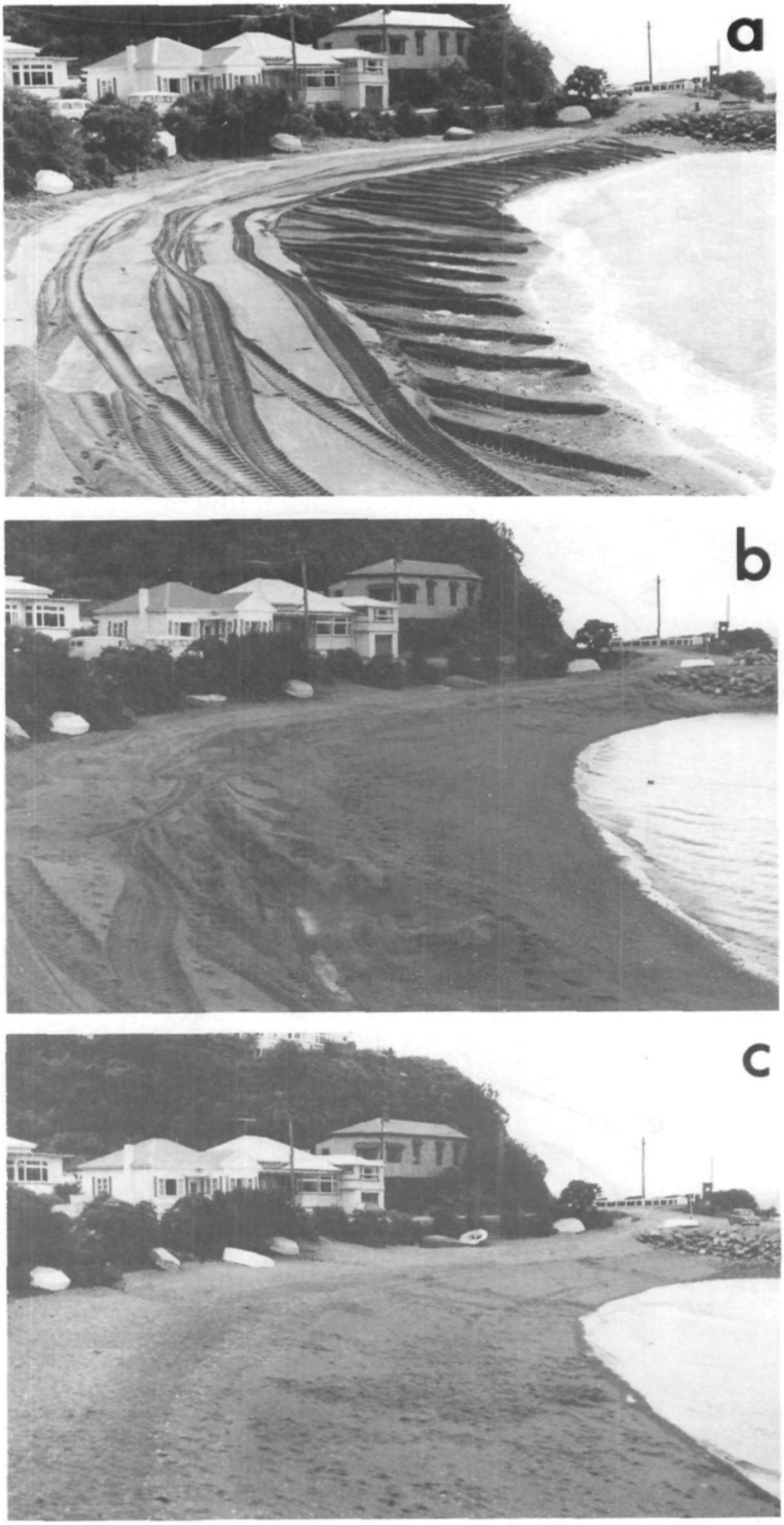


Fig. 6 Sequence showing the establishment of the beach face and berm just 16 days after dumping and mechanical grooming of nourishment sediment. Photograph **a** taken 18.10.82, **b** taken 21.10.82 after weak southerly wave attack ($H_{1/3}$= 0.1 m, $T_{1/3}$ = 1.2 s), and **c** taken 3.11.82 after gale-force northerly winds when waves were $H_{1/3}$ = 0.7 m, $T_{1/3}$ = 3.25 s.

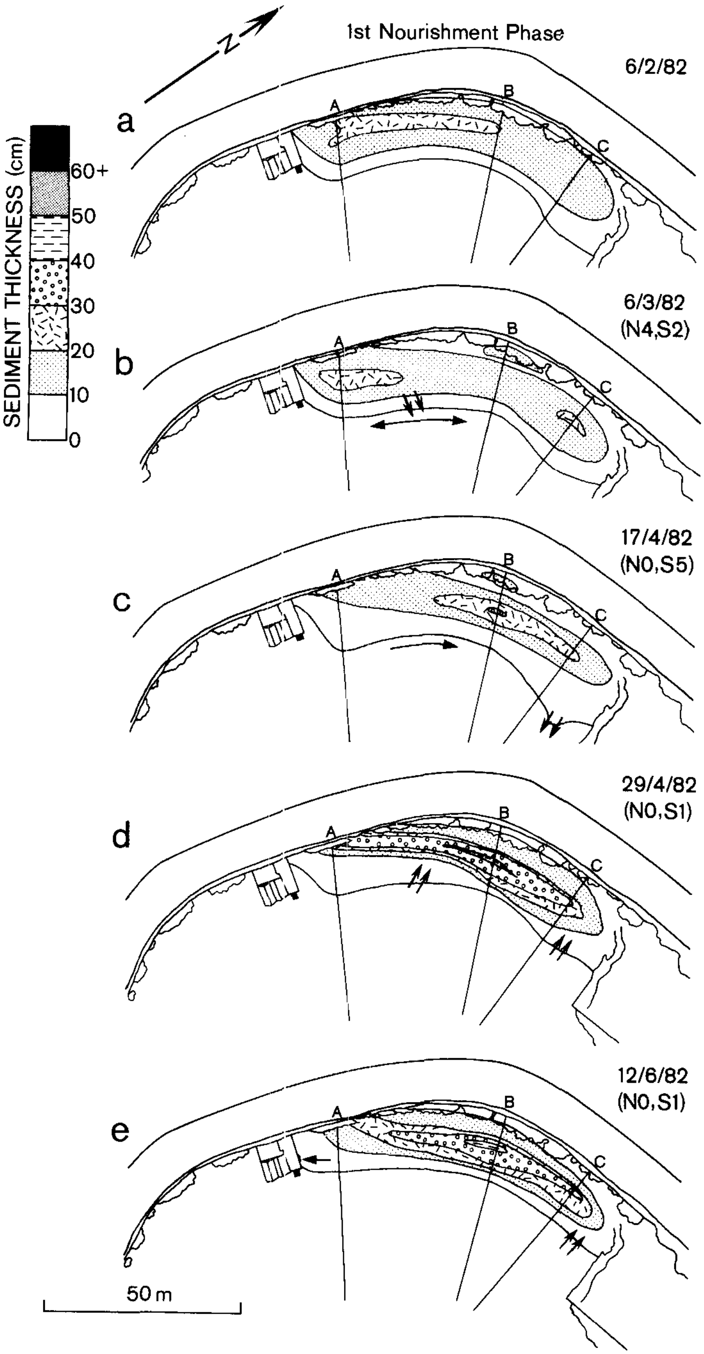
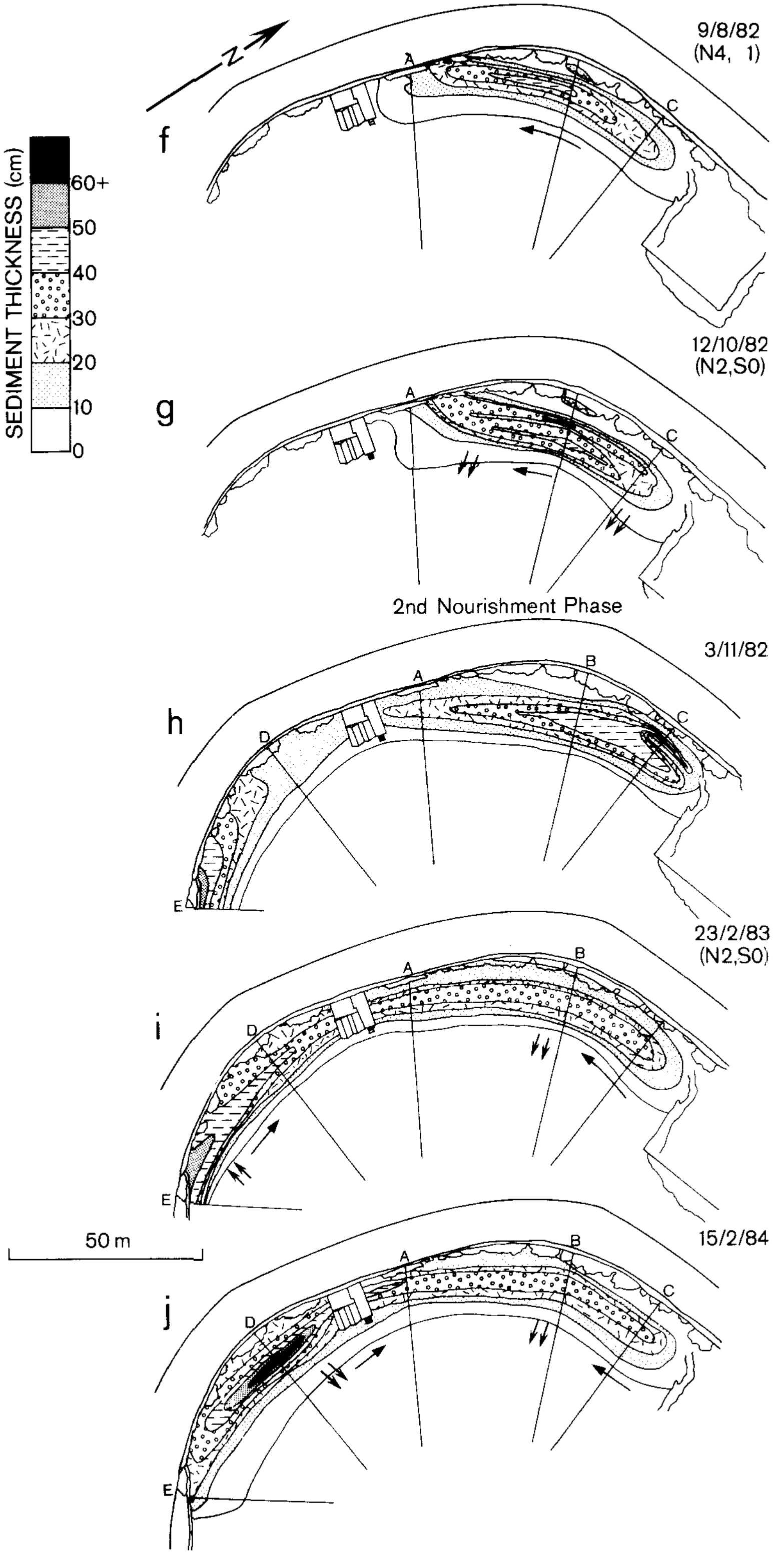


Fig. 7 Isopachs of sediment thickness for the introduced sediment after the first (8a–g) and second (8h–j) nourishment phases. The number of days with sediment-stirring waves (see Table 1) from the north and south for the week prior to each survey are presented in brackets, e.g., N4 = 4 days of sediment stirring waves from the north. Arrows denote directions of longshore and offshore/onshore sediment movement.

Fig. 7 (*Continued*)



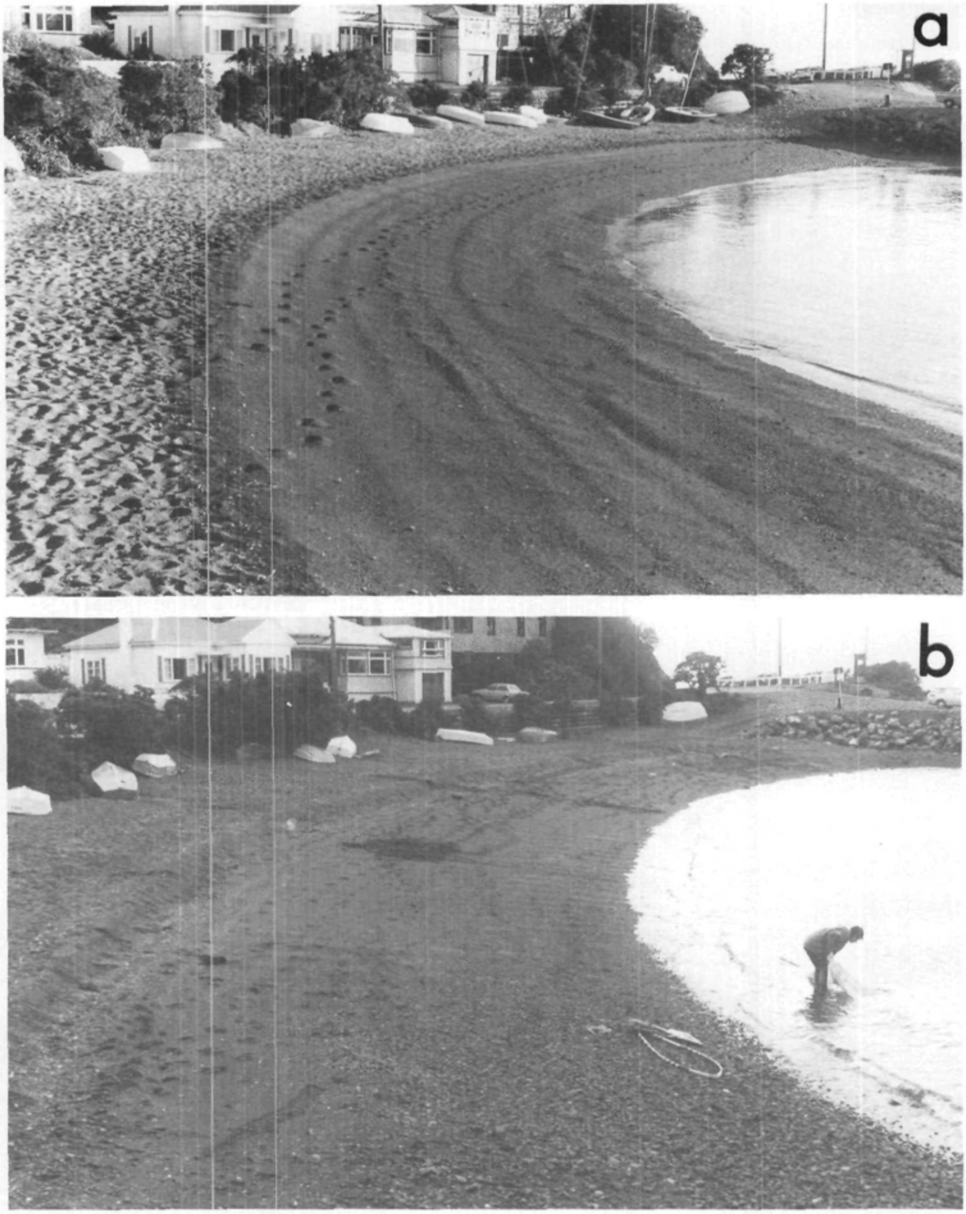


Fig. 8a Beach in the summer of 1982 just after the first nourishment phase and **b**, the same locality in the following winter after prolonged southerly wave attack which induced a northward transport (arrow) of nourishment sediment and exposed and pebble-cobble surface of the old beach in the foreground.

studies (Fig. 9). One month after dumping, the nourishment sediment had shifted a maximum of 20 m southwards under prevailing northerly wave attack — transport was concentrated at the zone of maximum swash which corresponded to a high spring tidal berm (Fig. 9a, b). High tides and northerly waves continued for the next two days and a subsequent survey recorded further southward growth along the berm at a rate of 1.6 m d^{-1} (Fig. 9b, c). By comparison, sediment at the beach face changed little in position.

The onset of intense southerly wave attack shifted the entire sediment cover, seaward of the berm at least 29 m to the north (Fig. 9d–g). Berm sediment

Table 1 Parameters of waves capable of moving coarse sand (0 φ, threshold, $\mu_m = 30$ cm s^{-1}) and granules (−2φ, threshold, $\mu_m = 55$ cm s^{-1}), in 0.5 m of water. Frequencies of these waves from the north and south are presented as a percentage of total time for 1982–83 and 1983–84.

	Height (m)	Period (s)	Bottom speed (cm s^{-1})	Wave frequency (% time)		
				Direction	1982–83	1983–84
Sand	0.2	1.75	35	North	48.2	49.3
				South	9.4	11.3
Granules	0.3	2.0	58	North	41.3	42.0
				South	4.8	6.9

eventually succumbed and it too migrated north of the changing sheds. By spring, northerly waves induced a small southward incursion of sediment but later changes were completely masked by the second dumping phase (Fig. 9 h–j).

Beach volumes

The total volume of the new beach, calculated according to Bannister and Raymond (1972), was 218 m^3 immediately after the first nourishment (Fig. 10). This figure agreed reasonably well with the total volume of truck loads estimated by the site engineer to be c. 250 m^3 (R. Nansen, Wellington City Council, pers. comm).

The total volume changed little up to the second nourishment phase, except for the loss of c. 50 m^3 recorded on two separate occasions in April 1982 (Fig. 10). This decrease is more apparent than real. Sediment and profile data record neither offshore nor longshore transport of sediment out of the study area at that time. Rather, the anomaly probably arose from a localised build-up of gravel between profile lines and its subsequent exclusion during volume calculations.

The second nourishment raised the beach volume to 528 m^3, 170 m^3 of which covered the beach south of the changing sheds. As before the total beach volume changed little, even 1.2 y. after the dumping (Fig. 10).

SEDIMENTARY CHANGES

Texture

Old and new beach sediments

The original beach sediment was a poorly sorted, polymodal gravel containing up to 90% cobbles, pebbles, and granules with an accessory component of fine to medium sand. By comparison, the new sediment was markedly finer grained and better sorted. At the time of beach nourishment, prior to any reworking by tides and waves, this introduced sediment analysed as a sandy gravel on the Folk (1965) classification with 12% fine pebbles, 47% granules, 41% coarse sand, and a mean grain size $M_z = -1.2$ φ. These components had a near-symmetrical distribution, i.e., near-zero skewness $Sk = -0.09$ and moderate to well-sorting values $\sigma = 0.70$ φ. Such characteristics were short-lived and the ensuing months witnessed a number of changes as the nourishment sediment adjusted to its new environment.

Textural variability

Changes in sediment texture with time and space are most conveniently summarised in a sequence of grain-size spectral plots (Fig. 11). More detailed time/space plots of mean grain size, sorting, and skewness are available from the authors on request.

Shore-normal variability is subtle and is restricted to a slight decrease in grain size and an improvement in sorting from the upper to middle beach followed by a reversal of these trends down to the lower beach where the edge of the nourishment sediment intermingled with the gravel substrate of the original beach (Fig. 11 a–c).

By contrast, alongshore textural gradients are distinct (Fig. 11d, e). The time-averaged spectral plots record a coarsening at both the north and south ends of Balaena beach. This trend resulted from an uncovering of the older beach as nourishment material shifted towards the beach centre, e.g., the mobile 2–3 φ sand fraction accumulated near Profile b, this build-up being particularly apparent a year after the second nourishment phase.

Superimposed on these broad geographic trends are fluctuations that presumably were caused by seasonality in the wave climate. Over the autumn and winter of 1982, the beach tended to become slightly finer grained and better sorted (Fig. 11a, b) except at the southern and seaward limit of the nourishment cover where old, coarse beach sediment was uncovered (Fig. 8a, 11c). This was a time of prevailing southerly waves, which, because of the restricted southerly fetch, tended to be less energetic than their northerly counterparts. In the

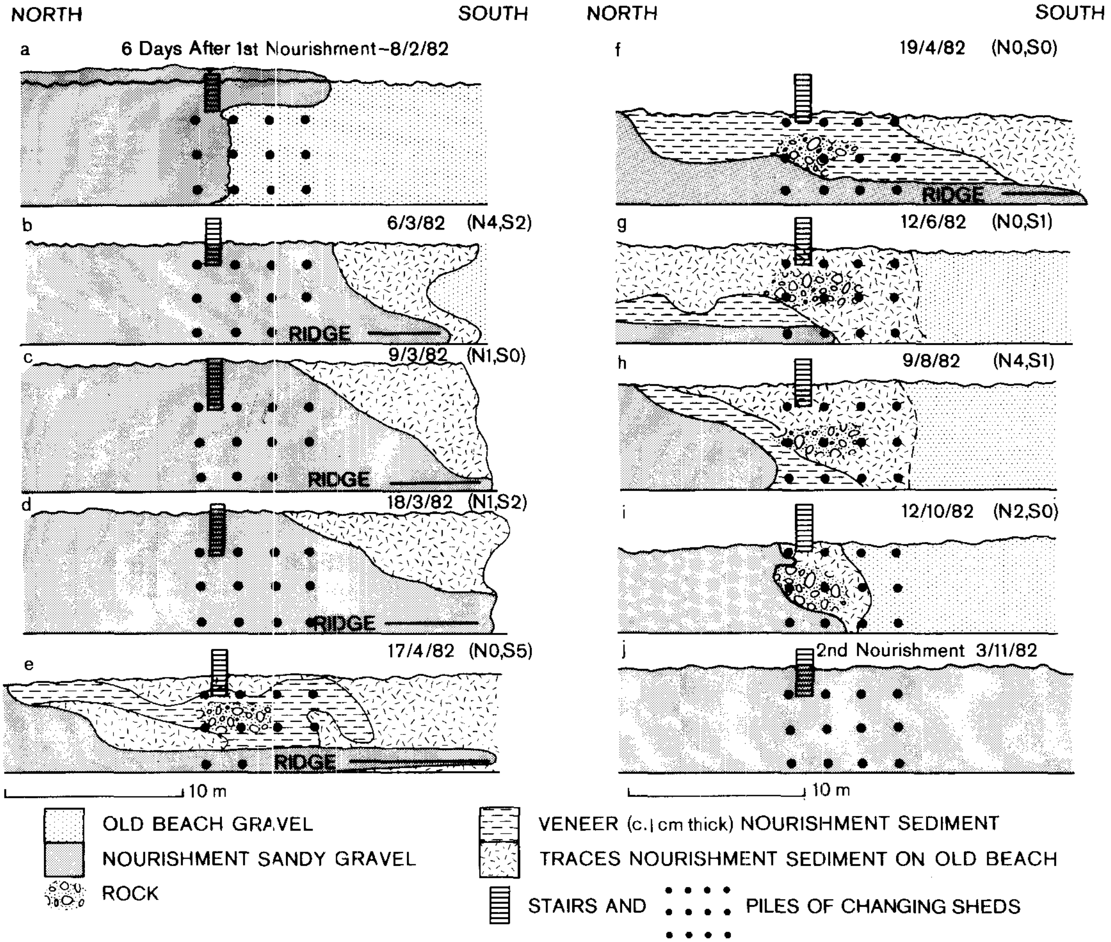


Fig. 9 Changes in plan outline of the southern limit of Balaena beach after the first nourishment phase (see Fig. 7a). The number of days with sediment-stirring waves from the north (N) and south (S) for an arbitrary one week prior to each survey are presented in brackets. For surveys < 1 week apart, the total number of days with sediment movement is given.

following spring prolonged northerly wave attack induced a coarsening of the nourishmet sediment particularly on the middle beach (Fig. 11b).

The second nourishment phase brought about a decrease in grain size that was followed a year later by an overall increase. This change largely reflected an uncovering and possibly mixing of original beach sediment into the nourishment material at both ends of Balaena beach.

Bay sediments

Sediments beyond low tide are predominantly well to moderately well-sorted fine sands with, gravel = 0.9%, sand = 98.9%, silt = 0.2%; M_z = 2.1 ϕ, σ = 0.8 ϕ, Sk = −0.16. Their grain size distribution is quite distinct from the nourishment material whose fine sand component seldom exceeded 0.5% during the entire monitoring period. A fine sand mode developed just once on the new beach, during the 1983 summer when a thin (< 1 cm thick) veneer of sand spread over parts of the lower beach.

The transition from beach to bay occurs abruptly over a distance of 7–14 m near the mean low tidal mark. Here the nourishment sediment thins out on the cobble-pebble surface of the old beach face which, in turn, gives way to the fine sandy bottom of the bay proper at c. 0.5 m water depth. Traces of nourishment sediment were detectable only at the landward limit of the bay sands.

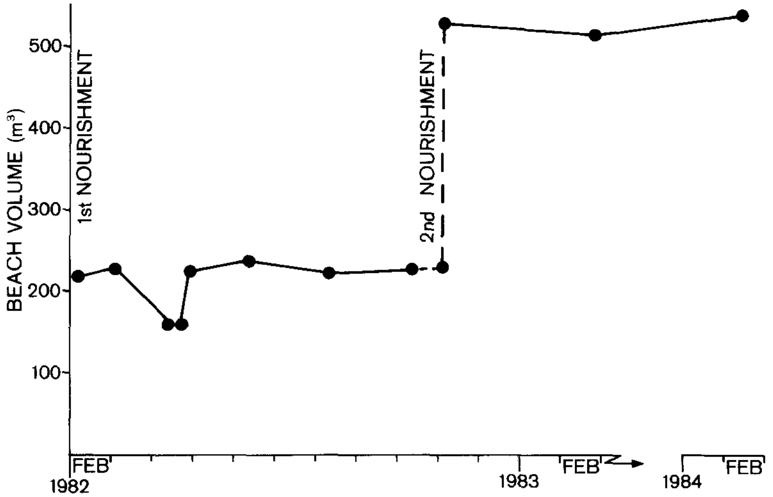


Fig. 10 Beach volumes calculated (according to Bannister & Raymond 1972) for the survey period February 1982–84. The apparent loss recorded in April is artificial, resulting from a highly localised build-up of sediment between profile lines.

Small quantities of gravel occur in bay sediments but their coarse size and iron-stained appearance indicate that these clasts were derived from the old gravel substrate rather than from the nourishment sediment.

Composition

Granule-sized components from a middle beach locality (O771) were sampled throughout the survey to determine any changes in composition relating to, for example, selective attrition of sandstone-argillite-quartz components, introduction of biogenic components, and mixing with original beach sediments.

Prior to the nourishment programme, sediments were dominated by clasts of sandstone (52%) with lesser amounts of argillite (16%) and quartz (21%) (Fig. 12a). A small (10%) but significant quantity of man-made debris including fragments of brick, concrete, glass, and asphalt was also recorded. Over 70% of grains were weathered, having heavily pitted surfaces and pronounced iron-stain.

The first nourishment phase brought about major compositional changes. The introduced sediment was predominantly rounded argillite clasts (55%) with sandstone and quartz present in subordinate amounts. Man-made debris was almost negligible (Fig. 12a). Furthermore, there were fewer and less intensely weathered clasts compared to the original sediment; introduced clasts typically having only a faint iron stain and little obvious surface pitting.

No major compositional changes were recorded over the survey period, the sediment of February 1984 was almost identical to sandy gravel introduced at the first dumping two years earlier (Fig. 12a). Nevertheless, some minor changes were evident, e.g., the quantity of heavily iron-stained sandstone clasts, derived from the original beach, diminished after each nourishment phase and then increased thereafter.

The calcareous biogenic component varied little over the survey period, ranging from 0–8% with $\bar{x} = 4.4\%$, $\sigma = 1.9$, $n = 16$ (Fig. 12b). Carbonate contents were least variable on the upper beach, most changes occurring to seaward. Although the data are sparse, the major fluctuations appeared to coincide with storms which, from field observations, tended to bring predominantly molluscan shell debris ashore where it was initially concentrated in strand lines. The principal contributors to this debris included *Aulacomya maoriana, Paphies australis, Chione stutchburyi*, and *Melographia aethiops* with small contributions coming from *Protothaca crassicosta, Mytilus edulis, Buccinulum lineum*, and *Turbo smargdus.*

Offshore sediments, by virtue of their fine grain size, are dominated by monomineralic grains, quartz, and feldspar. A minor, coarse sand-granule fraction is mainly calcareous shell debris with a few heavily iron-stained terrigenous clasts.

INTERPRETATION

Alongshore transport

Although Balaena beach is sheltered from ocean waves, the coarse sandy gravel is actively undergoing transport (Fig. 7, 9, 11). After the first nourishment, which covered north Balaena beach only, sediment initially moved northwards in response to the prevailing southerly wave attack of the

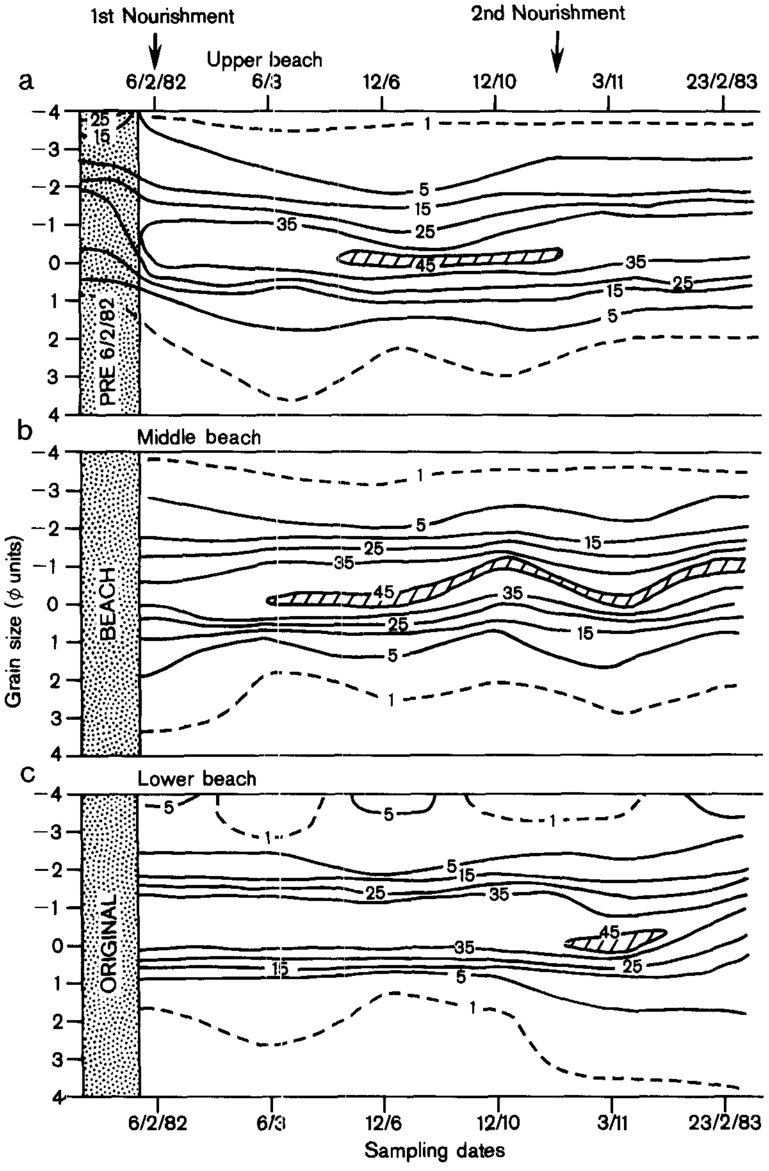
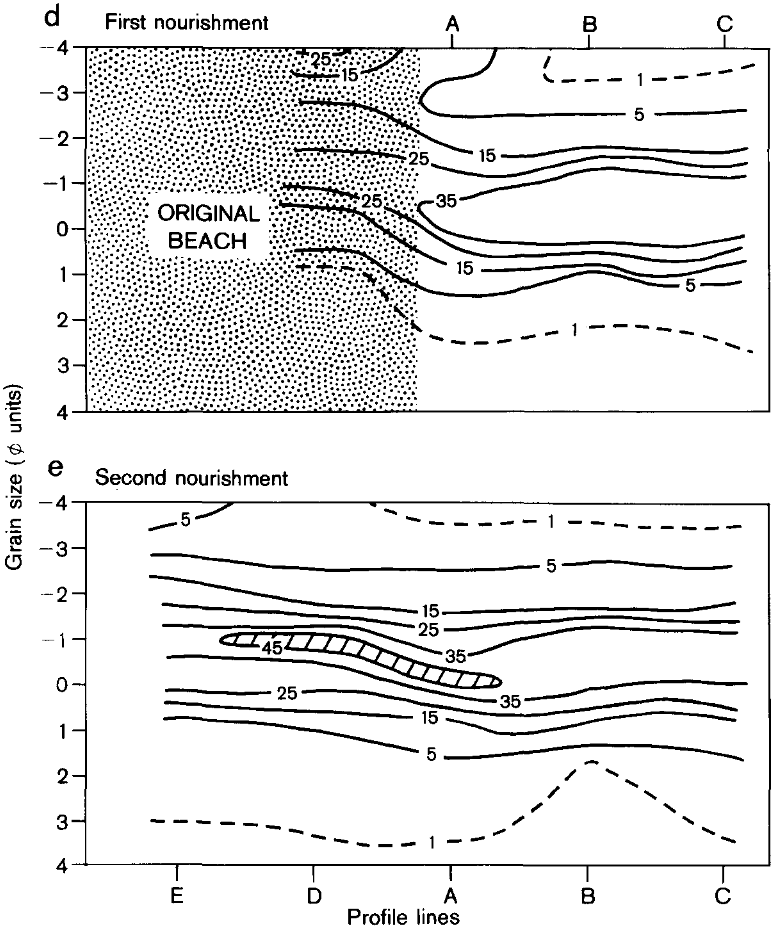


Fig. 11 Grain size spectral plots summarising time-variability across the beach (a–c) and time-averaged variability along the beach after the first and second nourishment phases (**d**, **e**).

autumn-winter months. In the following spring, as northerly waves gained ascendency, the net movement was southwards.

The basic simplicity of this picture was masked by the second nourishment which covered the entire beach. Four months after this event a convergent transport regime was evident with sediment from both ends of the beach having moved towards the centre (Fig. 7). Initially this convergence was regarded as the combined effect of alternating north/south wave directions. However, southerly waves played only a minor role. Those four months were overwhelmingly dominated by northerly waves as inferred from wind records which show northerlies as the strongest and most frequently occurring direction, accounting for 80% of winds with speeds > 20 km h^{-1} (New Zealand Meteorological Service 1983). The converging transport

Fig. 11 (*Continued*)



appears to be a consequence of the variable angle made by the curved shoreline with the direction of wave approach. Over most of Balaena beach northerly waves break at an angle to induce southward longshore drift. At the southern tip of the beach, however, wave refraction and shore curvature are such that the break angle is reversed and northerly waves induce a localised northward drift. This effect is heightened by the presence of a vertical, impermeable seawall which serves to translate breaking wave crests to the north.

Although the scattering of our observations preclude a precise appraisal of alongshore transport, an empirical assessment of transport frequency and magnitude may be made from the hindcast wave data, sediment threshold curves, and appropriate field observations.

The dominant sediment modes on Balaena beach lie between 1 and 4 mm diameter and, accordingly, have wave-induced thresholds of motion ranging from 30–55 cm s^{-1} (Komar & Miller 1973; Pickrill & Currie 1983). Waves capable of generating such near-bottom speeds, may be determined from Airy linear wave theory which defines near-bottom speed (μ_m) as follows:

$$\mu_m = \frac{\pi H}{T \sin h\,(2\pi d/L)} \qquad 1$$

where H = wave height, T = wave period, d = depth, L = wave length which here is defined for shallow water conditions by $L = T\,(gd)^{1/2}$, with g = gravitational acceleration (Komar 1976). By substituting the hindcast wave parameters (Fig. 4) into Equation 1 and using a depth of 0.5 m, corresponding to the water depth over the lower beach at middle tide, the minimum waves capable of shifting beach sediment were determined together with their frequency of occurrence (Table 1). For over half of 1982, beach sediment was in motion,

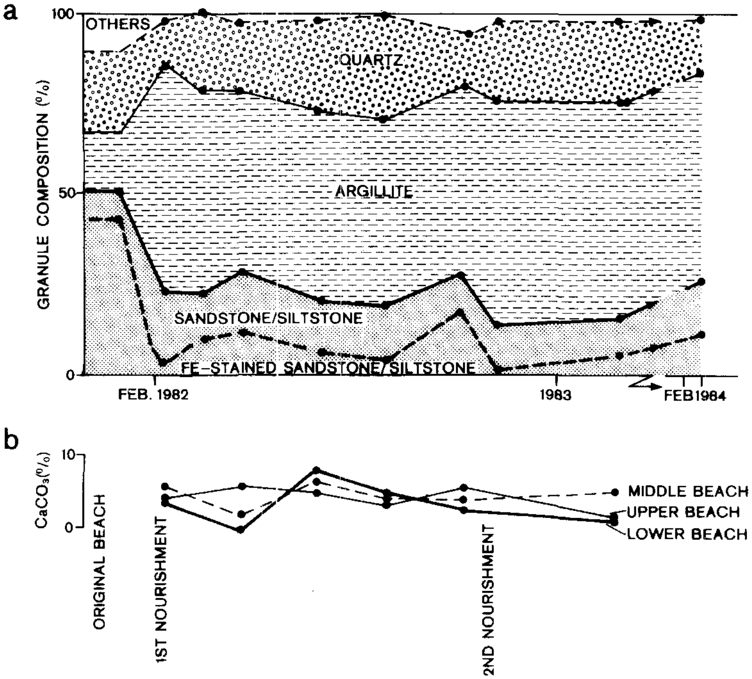


Fig. 12 Variations in granule composition (**a**) and total sediment carbonate content (**b**) at Station O771 over the February 1982–84 survey period. 'Others' category includes primarily man-made debris such as bottle glass, brick, concrete, and asphalt.

chiefly under the effects of northerly waves. Southerly waves, although making their impact felt in the autumn-winter, accounted for only 9% of the time because of the lower frequency of southerly winds and the shorter fetch of the wave generating zone. Although 1983–84 had a slightly higher incidence of sediment-stirring waves, these waves were smaller than those of the previous year. Furthermore, 1983–84 had a reduced north-east wave component and the beach suffered less direct wave attack (Fig. 3). This perhaps accounts for the similarity between the February 1983 and February 1984 isopachs (Fig. 7i, j).

This theoretically assessed variability is verified by field observations which show the beach readily responded to sediment-stirring waves on a monthly and even daily basis, e.g., Fig. 9b–c, e–f.

Comparison of volumetric gains and losses at each profile site permit some estimation of net longshore transport rates. Over the first eight months following the first nourishment there was a net average northward transport of 3 m^3 $month^{-1}$ for the beach north of the changing sheds. The second nourishment was followed by an average southward drift of 2.9 m^3 $month^{-1}$ for the same stretch of beach (i.e., Profiles a–c), whereas the beach south of the changing sheds recorded a counter drift also of 2.9 m^3 $month^{-1}$.

Evidence of longshore transport is also manifest in the textural data. As sediment is eroded and transported either north or south, preferential deposition of coarser grains occurs along the transport path, e.g., the northward drift following the first nourishment was accompanied initially by deposition of granules and then deposition of coarse sand further updrift. This pattern reversed under southerly waves. As anticipated, fines were depleted and coarse sediments of the old beach were exposed and incorporated in the new cover (Fig. 8).

Onshore-offshore transport

Morphologic and textural data revealed that shore-normal movement of sediment was confined to the new beach. Beach width fluctuated between surveys culminating in a maximum widening of 8 m between February 1983 and February 1984. Similarly, there were landward and seaward changes in the loci of deposition as manifested by the sediment isopachs (Fig. 7). Little sediment was exchanged between the beach and bay floor. The fine quartzo-feldspathic bay sands are almost devoid of the coarse lithic clasts characteristic of the nourishment sediment. Conversely, the beach receives only small quantities of bay sand as witnessed by the rare occurrence of a fine sand mode in beach grain size distributions and the continued exposure of the old beach surface between the new beach and bay sediments.

Sediment budget

Beach volumes remained reasonably stable after each nourishment phase indicating either new sediment remained on the beach intact or the beach suffered changes which were compensated by sediment losses or gains from elsewhere (Fig. 10). With respect to the latter alternative, two possibilities exist: sediment is gained through longshore drift, onshore transport, and biogenic productivity or sediment is lost through offshore transport, grain attrition, and longshore drift.

As noted in the preceding section, there is little exchange between the bay and the beach. Similarly, exchange through longshore drift around the headlands of the bay is negligible as shown by a dearth of new beach sediment in the updrift areas such as the periphery of the reclamation.

The beach periodically received gravel-sized biogenic debris which was usually concentrated along strand lines of the middle beach and presumably represented the remains of bay inhabitants swept ashore during storms. Yet despite these periodic incursions, the beach biogenic components, as measured on six separate occasions, remained low and fairly consistent suggesting supply was roughly matched by a loss of shell debris (Fig. 12b). We surmise that the brief influxes of debris are matched by a long term removal of soft-shell material by attrition amongst the more robust lithic clasts, e.g., Pettijohn (1956), Blatt et al. (1972). The resultant comminuted debris is swept offshore as inferred from the occurrence of sand-sized shell debris in the bay sediments.

Apart from the likely attrition of biogenic gravel, the remaining beach components (sandstone, argillite, quartz) record no major changes in their proportions and, therefore, can be assumed to have been stable over the two year monitoring period.

Returning to our opening statements on the beach budget we conclude that the bulk of the introduced sediment has remained intact. Some gains and losses of sand and gravel have occurred, e.g., supply and removal of biogenic debris, but these are small accounting for less than 10% of the total budget.

CONCLUDING REMARKS

The nourishment of Balaena beach has been a success, at least over the two year monitoring period. The survey demonstrated that a coarse-grained beach within the protected waters of a harbour, may still exhibit considerable mobility. Yet despite such movement, the introduced sandy gravel remained on the beach (there was little alongshore and offshore loss of sediment).

Because sediment mobility is controlled primarily by locally generated wind waves, it is pertinent to examine the findings in the context of long-term weather patterns for this will provide some insight into future beach stability. The first year of observations coincided with a major perturbation of the Southern Oscillation, e.g., Gill and Rasmusson (1983). The global impact of these events was felt in the microcosm of Balaena Bay where the beach suffered unusually frequent and prolonged periods of intense wind-wave attack which in turn produced pronounced bouts of alongshore transport. By comparison, 1983–84 was a less unstable meteorological period and the beach reacted accordingly with less pronounced changes. The point is that our monitoring period included a major meteorological disturbance and yet Balaena beach remained intact. We can, therefore, view the future of the beach with some confidence. However, knowing the fickleness of Wellington weather, a particularly intense event such as the 1968 *Wahine* storm (e.g., see Jamieson 1968) could bring about major and, perhaps, irreversible changes to the beach.

Although the beach has remained intact, management of this recreational resource is still required. Longshore drift is currently exposing the undesirable old beach surface at the same time causing sediment build-up elsewhere. This situation could readily be remedied by mechanical 'beach grooming'. Sediment from the depocentres could be used to cover exposed sections of the beach. Occasional dumpings of new sand may also be required as sediments gradually abrade to grain sizes too unstable to remain in the littoral zone.

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