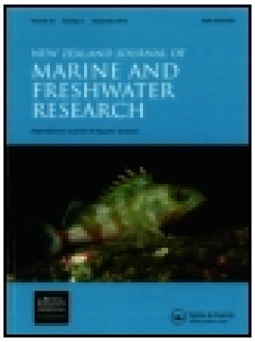

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Sedimentary processes operating around the entrance to a river mouth port, Westport, New Zealand

ROBERT M. KIRK[1]
WAYNE J. HASTIE[2]
JOHN L. LUMSDEN[2]
[1]Department of Geography
University of Canterbury
Private Bag, Christchurch
New Zealand
[2]R. W. Morris and Associates
Consulting Engineers Limited
P. O. Box 8074, Christchurch
New Zealand

Abstract The paper presents investigations of wave climate, tidal inlet hydraulics, and sand sediment bypassing at the entrance to Westport Harbour, South Island, New Zealand. The results complement and extend those of studies of bar morphologies and sediment characteristics already published. Longshore transport of about 1×10^6 m^3/year is directed in a net eastward fashion across the inlet because of an in-built misalignment of the harbour training walls. Approximately 90% of the drift is bypassed, and has been since 1921, by deflection and splitting of the main sediment streams through the inner and outer bars and a transverse channel across the entrance. The outer bar appears to be the submarine, downdrift extension of Carters Beach and river load appears to contribute an order of magnitude less sediment to the complex than annual littoral drift. River sediments and littoral drift are mixed off the harbour and a declining proportion over time is recirculated to cause progradation of North Beach. The tidal compartment contributes little to scour of the entrance because of the predominance of bar bypassing. Contrary to the recommendations of several past studies, it is argued that improvements in navigation depths at Westport are more likely to be obtained through modification of the littoral drift system than they are from tidal compartment enlargement.

Keywords Westport; river mouth port; river mouth bars; sediment bypassing; tidal hydraulics; inlet stability; beach accretion; wave climate

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INTRODUCTION

The operational efficiency of the river mouth port of Westport, New Zealand (Fig. 1), is often limited by changing bar formations at the entrance. Many attempts have been made to improve conditions but to date all have resulted only in short-term benefits. The most frequently adopted solution has been training wall development (see Kirk et al. 1986), although bar dredging has also been undertaken. One solution favoured by many reports (e.g., Rendel et al. 1946), but which has never been adopted, is tidal compartment enlargement.

Because the problems at Westport result from sediment movement in the entrance area it is considered essential to gain an understanding of the sediment transport regime so that possible solutions can be evaluated. For this reason a comprehensive sediment investigation was undertaken. The results from this investigation are presented in two parts.

Firstly, harbour entrance morphologies, sediment characteristics, and inferred sediment transport paths have been described in Kirk et al. (1986). Briefly, the most frequent morphology found was that in which two submarine bars were present off the river mouth. When present, these bars were separated by a transverse channel running east from Carters Beach and terminating in the principal inlet channel (see Fig. 1). Data from analysis of sediment sizes, particle shapes, and mineralogies suggest that longshore sediment transport is predominantly from west to east and that river derived sediment is deflected to the east. The inner bar is believed to be predominantly a littoral drift related event whereas the outer bar, which is composed mainly of littoral drifted sediment, forms as a submarine extension of Carters Beach. Both bars can be modified by floods in the river, although modification of the outer bar is much less frequent because of the very high river flows required. Sediment can bypass directly across the river mouth only when the inner bar is present. On other occasions bypassing can only occur by transport through the transverse channel or over the outer bar, into the river channel and thence onshore.

Secondly, the processes operating to produce these morphological features and sediment transport patterns are described in the present paper. This is done by examination of the wave climate, littoral drift, and Buller River characteristics, followed by investigations of tidal hydraulics and inlet stability, and of sediment bypassing and beach growth adjacent to the inlet.

WAVE CLIMATE

A comprehensive description of wave height and period characteristics at Westport is presented by Valentine & Macky (1984). Other data, based on visual observations from the shore, are presented in Mangin (1973). Valentine & Macky collected wave records with a Datawell waverider accelerometer buoy at a site 2.8 km off North Beach from 25 August 1980 to 17 February 1983. The average significant wave height (H_s) was 1.16 m and the average zero-crossing wave period (T_z) was 7.5 s. A scatter diagram showing H_s *versus* T_z showed that the most frequently occurring combination was H_s, 0.5–1.0 m and T_z, 6–7 s. A power spectral density graph for the Westport data indicated that the greatest concentration of wave energy corresponded to a wave period of about 14 s.

A general indication of wave directions in the Westport area can be obtained from the analysis of ship reports in the grid square 40.0°–44.9° S, 170.0°–174.9° E (Reid & Collen 1983). Between 1957 and 1980, 4037 observations were made and the results showed that westerly swell waves predominated (27%), followed by south-westerly (21%), north-westerly (13%), and northerly (10%).

More detailed information on wave approach directions was obtained from refraction analyses. Refraction diagrams were produced graphically using the wave front method of Johnson et al. (1948) for the deep-water approach directions listed above. Two wave periods were selected; firstly, the average zero-crossing period (7.5 s) and secondly, the period corresponding to the greatest concentration of wave energy (14 s), as measured by Valentine & Macky (1984). Inspection of the resulting diagrams showed that the alignment of Carters Beach is generally close to equilibrium with wave approach directions for the longer-period waves, but that the shorter-period waves are incompletely refracted. The diagrams also showed that the waves travel at an angle across the harbour mouth thereby promoting an eastward drift of sediment across the entrance. The fact that seas approached the harbour at an angle was noted as early as 1892 (Furkert 1947) but no action has ever been taken to alter the alignment of the entrance.

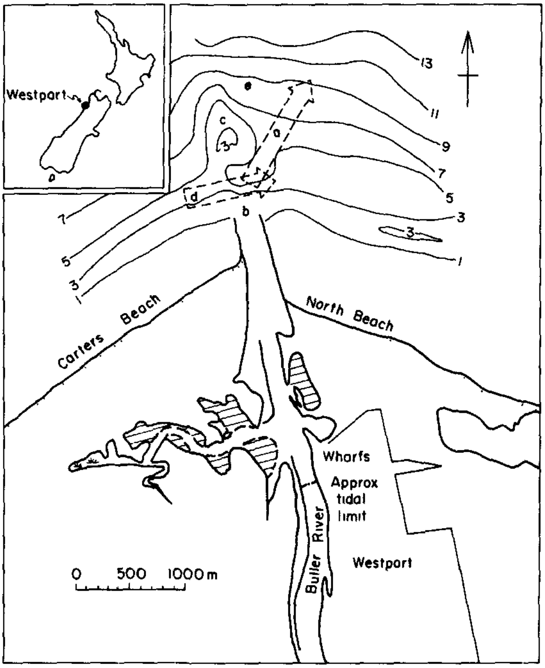

Fig. 1 Locality map of Westport Harbour, South Island, New Zealand. Bathymetry is in metres below chart datum as surveyed in March 1984. Features are: a, principal inlet channel; b, inner bar; c, outer bar; d, transverse channel; e, dredge dump ground. Shaded areas represent tidal mud flats.

LITTORAL DRIFT

Wave data from Reid & Collen (1983), Valentine & Macky (1984), and the refraction diagrams have been used to estimate a longshore transport rate at Westport and to determine the approximate width of the longshore transport zone.

Hallermeier (1981) calculates the approximate seaward limited (dl) of extreme surf related effects so that significant longshore transport and intense on-offshore transport are restricted to water depths less than dl:

$$dl = 2\,H_s + 11\sigma \qquad (1)$$

where dl = seaward limit of extreme surf related effects, H_s = the average significant wave height, calculated from at least one full year of data, and σ = annual standard deviation of significant wave height.

Using Westport wave data from Valentine & Macky (1984), dl was 9.91 m. Intense sediment transport at Westport is, therefore, restricted to a zone running from the shore seaward to a depth of about 10 m, which is reached c. 1.4 km offshore. This zone includes most of the bar complex (see Kirk et al. 1986).

An estimate of the longshore transport rate at Westport was calculated from the CERC energy flux formula (US Coastal Engineering Research Center 1977):

$$Q = K (H_b)^2 C_b \sin 2 \alpha_b \qquad (2)$$

where Q = longshore transport rate (m^3/year), K = coefficient and units conversion factor = 0.79×10^6, H_b = breaking wave height (m), C_b = breaking wave celerity (m/s), and α_b = breaking wave angle (degrees).

Breaking wave angles were measured from the 7.5 s refraction diagrams for a point on Carters Beach 1 km west of the harbour entrance. Breaking wave height was taken as 1.16 m and longshore transport rates were calculated for south-west, west, north, and north-west deep water wave approach directions. These rates were then converted to annual values by a corrected percentage of occurrence using the values presented above from Reid & Collen (1983) and assuming that the occurrence of these four directions totalled 100%. The converted transport rates were then summed to give a resultant net transport of 0.9×10^6 m^3/year to the east. For the purposes of the study a longshore transport rate of 1.0×10^6 m^3/year was adopted.

The adopted longshore transport rate is considerably lower than some of the previous estimates made for Westport. Furkert (1947), for example, estimated that the transport past Westport was 3.8×10^6 m^3/year. This rate was determined in part from the growth of Farewell Spit, about 180 km to the north of Westport, and it is, therefore, considered to be unreliable. Other rates were calculated from measured bathymetric changes (e.g., Simpson 1959). Such measurements represent gross changes over an area and as such are not transport rates.

BULLER RIVER CHARACTERISTICS

Buller River flow data are presented in Table 1. The mean river flow is 416 m^3/s.

A procedure for calculating river sediment yield is presented by Griffiths (1979, 1981). This procedure gives an annual average total load of 1.07×10^6 m^3/year for the Buller River. It is assumed here that c. 15–30% of this load is in the sand size range and therefore the river will be contributing c. 107 000–214 000 m^3/year to the bar area. These figures suggest that the river contribution to bar sedimentation is very much smaller than that of the longshore drift, a finding in line with earlier findings from the analysis of the morphology and sediments of the entrance area (see Kirk et al. 1986). This finding notwithstanding, it is likely that large variations in both littoral drift and river load occur over time.

Table 1 Buller River flow data. From Mangin (1973) and Griffiths (1981).

Flow condition	Discharge (m^2/s)
Minimum flow	99
Mean flow	416
Mean annual flow	4500
Ten-year flood	6345

TIDAL HYDRAULICS AND INLET STABILITY

According to Bruun (1978), the term "stability" can be applied to an inlet in two distinct senses, first the stability of the entrance throat cross section (of which depth is the dimension of most interest), and secondly the stability of the entrance channel with respect to a location and number of distributaries. Since Westport has a single throat channel confined between training walls the second definition is not applicable to the inner bar, though it may have relevance for the outer bar where morphological variations are known to occur (Kirk et al. 1986). A third aspect of stability concerns the equilibrium length of the entrance channel. Bruun & Gerritsen (1960) and Bruun (1978) discuss this aspect in general terms and note that it is possible for an entrance channel to be inefficiently long in respect of sedimentation processes but they present little quantitative guidance on the manner in which this aspect of stability should be assessed. For this reason channel length at Westport is noted as an important but as yet unevaluated aspect of the harbour sedimentation problems.

The stability analysis that follows applies strictly to the immediate area of the training wall ends. Because of outflow/wave interactions and sediment recirculations over a wide area there may only be an indirect association between inlet flow dynamics and sedimentation over much of the bar area.

Bruun (1978) demonstrates that most entrance sedimentation problems relate to the manner and efficiency with which sands are moved across the inlet. Two types of bypassing are common. In some situations sand fed to the inlet is entrained by the flood tide, carried into the estuary or harbour (where some portion may be deposited), and then jetted out again on the ebb and released to the littoral drift to move down coast. This is termed *tidal bypassing* and is usually associated with larger tidal ranges and poor bar development. In other situations a prominent bar is present and sand bypasses to the downdrift shore by transport through the bar under combined wave and current action. This is termed *bar bypassing* and is common in lower tidal ranges. In yet other situations a combination of tidal and bar bypassing is known.

One index of inlet stability presented by Bruun (1978) is the ratio of the tidal compartment (Ω) to the annual longshore drift reaching the inlet (M). This index can be used to determine the type of sedimentation regime operating.

Bruun has established the following general guides for the ratio Ω/M:

$\Omega/M \sim 150$: Good entrance conditions, little bar and good flushing — tidal bypassing dominant.

$\Omega/M = 100–150$: Less satisfactory, offshore bar formation more pronounced. Mixed tidal/bar bypassing.

$\Omega/M = 50–100$: Entrance bar may be large but there is usually a channel through it.

$\Omega/M = 20–50$: Typical bar bypassing inlets. Waves break on the bar in storms. Inlets "stay alive" by periodic flushing from river floods, monsoons etc. Wild and dangerous for navigation.

$\Omega/M \sim 20$: Entrance is unstable, "an overflow channel" rather than a permanent inlet.

Although Bruun (1978: 432) states that there is no formal relationship between tidal compartment and entrance bar depths there is a loose association which he specifies:

$\Omega/M > 150$: bar depths 5–9 m range

$\Omega/M = 100–150$: bar depths 3–6 m range

$\Omega/M < 60$: bar depths 1–3 m range

Before these relationships could be used to assess bar conditions at Westport it was necessary to add the river discharge to the tidal compartment (Ω) to obtain the total discharge through the inlet (Ω'). Data on the tidal compartment were derived from Ministry of Transport drawings. The values found were 4.65×10^6 m^3 for the spring ebb tide and 2.44×10^6 m^3 for the neap ebb tide. No check on the accuracy of these values has been possible but it will become apparent that very large errors would be required to cause appreciable differences in the entrance stability ratios. River discharges for a range of flow conditions were calculated for a half tidal cycle (6.25 h) from the data in Table 1. The total longshore drift reaching the inlet (M) was approximated from the value of Q calculated from Equation 1.

Details and results of the analysis are presented in Table 2. The first row of the table shows the influence of the tide alone ($\Omega'/M = 2$ to 5). Clearly the tidal contribution to stability is extremely small and were the harbour to be a natural one with little freshwater inflow it would have an entrance amounting to little more than a storm beach wash-over fan.

For known flow conditions at Westport the stability ratios range from 2 to 147, underlining the wide variation in entrance and bar conditions known to occur. However, it is abundantly clear that Westport Harbour is pre-eminently a *bar bypassing* system. Even the largest floods down the river (such as the 10-year flood) result in only fair to good stability for short periods of time.

The range of stability ratios presented in Table 2 is in good agreement with both the observed bar depths at Westport and the broad groupings of ratios and depths proposed by Bruun (1978). Analysis of water depths for 1956–1980 and ongoing surveys show that inner bar depths at Westport can range from less than 2 m to more than 8 m. Greater depths follow major floods in the Buller River and conditions rapidly and persistently return to the shallow end of the depth range, regardless of the form and depths over the outer bar. Comparison of Bruun's criteria with Table 2 suggests that inner bar depths in the 1–3 m range are to be expected for events exceeding the mean annual flow in the river, but less than the mean annual flood.

Under river flow conditions less than the mean annual flood, flushing of the entrance is extremely poor and the littoral drift is the dominant control of the bar size and form. Given that the river sand contribution is not large it is also evident that littoral drift is the major contributor by volume for most flow conditions.

Flow events larger than the mean annual flood will improve entrance conditions but the improved conditions may be of a short duration only because

Table 2 Westport Harbour entrance hydraulic stability and extent of bar sand bypassing under a variety of hydrological flow conditions. Ω', total discharge through the inlet during one half tidal cycle; M, total annual longshore drift reaching the inlet.

	Flow events	River discharge ($m^3 \times 10^6$)	Tidal discharge ($m^3 \times 10^6$)	Ω'/M
Tide only	Neap	—	2.44	2
	Spring	—	4.65	5
River plus tide	Minimum flow + neap	2.23	2.44	5
	Minimum flow + spring	2.23	4.65	7
	Mean flow + neap	9.36	2.44	12
	Mean flow + spring	9.36	4.65	14
	Mean annual flood + neap	101.25	2.44	103
	Mean annual flood + spring	101.25	4.65	106
	Ten-year flood + neap	142.8	2.44	145
	Ten-year flood + spring	142.8	4.65	147

heavy westerly or south-westerly swell can rapidly rebuild the inner and outer bars.

It is clear from the stability analysis that it makes little difference whether river floods occur at neap or spring tidal conditions. The effect of tidal phase is greatest for river flows around and slightly above the mean flow, so that long intervals of average flows will permit bar build-up by littoral drift with increased intensity during neap tides provided the requisite sea states occur in conjunction.

However, for low-flow conditions in the river there is an important aspect to scour within the harbour channel because it is evident from diving observations that salt water wedge formation on the rising tide limits scour of the channel and enhances deposition of any suspended load from the overlying river water (Kirk et al. 1986). Scour of the channel can thus be expected to be at a maximum at low water rather than at mid-ebb tide when the combined salt and freshwater discharge would be greatest.

It is clear from the above analysis that tidal scour of the entrance is ineffectual at most discharge states. Many previous studies of the Westport Harbour entrance problems have recommended tidal compartment enlargement (e.g., Rendel et al. 1946), therefore it is instructive to examine the influence of the tidal compartment on stability ratios over time. This has been done using additional tidal compartment data computed from Furkert (1947) and the results are presented in Table 3.

It can be seen that though there was a large apparent reduction of the compartment (by 24.8%) *between 1892 and 1947, the stability ratios for given* flow states have been much the same throughout the history of the harbour. Tidal scour was never a very potent force at the inlet in either its natural or its modified state. At flow equal to the mean annual flood in 1892 the stability ratio would have been about 107 which compares with about 106 presently (see Table 2). It follows that little could be gained from modification of the tidal compartment, (e.g., by dredging). The necessary change can be roughly calculated from the data in Table 2. On the basis that good stability with few bar problems would be achieved at $\Omega'/M = 150$ and that it would be desirable to achieve this condition for flows not less than the mean river discharge plus spring tides, the "tidal compartment" would have to be increased from its present value of 14.01×10^6 m^3 (4.65×10^6 tide + 9.36×10^6 river, see Table 2) to a total of 150×10^6 m^3. The tidal component would be $(150 - 9.36 = 140.64) \times 10^6$ m^3 and the increase would be $140.64/4.65 = 30.2$ times. Such an enormous increase would be both impractical and uneconomic. It is, therefore, concluded that tidal considerations can be largely deleted from assessments of future options for improvement of navigation and operational conditions at Westport.

Table 3 Historical stability of Westport Harbour entrance. Tidal compartment data derived from Furkert (1947) and Ministry of Transport plans. River flow data from Table 1. Ω', total discharge through inlet during one half tidal cycle: M, total annual longshore drift reaching the inlet.

		Tidal compartment		
Date	Flow events	area (ha)	% decline	Ω'/M
1892	Mean flow + 3 m rise (approx. HWOST)	204.4		16
1947	Mean flow + neap	153.8	24.8	15
	Mean flow + spring	153.8	24.8	19
	Mean annual flood + spring	153.8	24.8	111
1979	Mean flow + neap	152.6	0.8	12
	Mean flow + spring	152.6	0.8	14
	Mean annual flood + spring	152.6	0.8	106

As for the tidal compartment, it is possible to broadly quantify the effects of littoral drift modifications on the stability ratios. Table 4 sets out the littoral drift reductions necessary to achieve the ratio $\Omega'/M = 150$ (bar depths in the range 5–9 m) for a range of discharge states at the entrance. It can readily be seen that for flows of the mean annual discharge and less, reductions of up to 90% would be necessary. However, a very favourable decrease in the proportion occurs from 90% to about 30% *for events between the mean discharge and the* mean annual flood. It seems that very useful improvements in bar depths might be obtained by effectively reducing the longshore drift by 30% or more (some 300 000 m^3/year). Such a reduction might be achieved in a number of ways involving structures, modification of the refracted wave field, dredging, bypassing, or some combination of these methods. For less stringent requirements, for example, a stability ratio of 80 which should be associated with inner bar depths in the range 3–6 m, correspondingly smaller drift reductions would be required.

SEDIMENT BYPASSING AND BEACH GROWTH

Within the broad context of the hydraulic controls discussed above it is important to establish the quantities of sand presently bypassing the entrance and to show how the harbour structures have interacted with the sea states, the littoral drift, and the river flows to produce the known historical patterns of beach growth and bar build-up. This has been done by analysis of old surveys, particularly of the beach, and by application of a mathematical model for the interruption of littoral drift by the training wall structures.

This is important because it is common on drift coasts for longshore transport to be strongly directed (in net) in one direction along the coast. The imposition of a barrier such as the Westport training walls normally leads to a "groin effect" on such coasts and the result is updrift accumulation and downdrift sediment starvation accompanied by erosion. It has already been shown that the Westport training walls have an in-built alignment that assures a continuing cross-inlet transport potential.

At Westport the dominant drift has been argued to be eastward but beaches to both the west (updrift) and the east (downdrift) of the structures have shown strong growth (Mangin 1973; Gibb 1978), apart from minor phases of storm erosion such as documented for North Beach by Nevins (1938). Since the bar forms and the wave analysis were unequivocal in respect of the strong eastward drift considerable recirculation and counterdrift of sand on the eastern shore are indicated.

Beach accretion 1870–1979

Low water ordinary spring tides (LWOST) shorelines were mapped from a variety of sources and the sediment volumes stored landward of this contour were calculated for about 1.4 km of both Carters Beach and North Beach. The results are presented in Table 5 from which it can be seen that some 6.43×10^6 m^3 accumulated west of the training walls after 1870 and 6.97×10^6 m^3 were gained to the east, a total of 13.4×10^6 m^3 on 2.8 km of beach. The total accumulation areas extend over about three times this length of shore on each beach, a fact taken into consideration later. It is interesting that more sediment has accumulated "downdrift" of the training walls than "updrift" (Mangin 1973; Gibb 1978), a feature which reflects nourishment of the eastern shore by both bypassed recirculated drift and the river load, as will be demonstrated later. It should also be noted that extensive and regional shoreline erosion north of North Beach occurs in gravel beaches (Gibb 1978) and has a long history largely unrelated to harbour development (Mangin 1973).

The accretion values for 1870–1879 are probably overestimates because the 1870 map merely indicates a "shoreline" which bears an unknown relationship to LWOST. However, the three surveys before commencement of training wall construction (first phase 1886–1891) reveal an important fact. The "natural" shorelines of the Westport inlet were highly unstable and were undergoing very rapid accretion *before* the insertion of any obstructions to the littoral drift. Natural bar bypassing on an accreting shore is an interpretation also supported by the entrance stability ratios. The development of the training walls has thus complicated a natural phenomenon rather than generated an entirely new bypassing system.

Table 5 shows that the net accumulation rates have fluctuated over time on a generally falling trend and that at some times North Beach gained faster than Carters Beach whereas the relationship was reversed in favour of Carters Beach at other times. The significance of these fluctuations is not clear but the overall decline in accumulation on both beaches is very important because it suggests that the history of both beaches is a long-term response to the initial phase of harbour training wall construction, later extensions having comparatively minor effects; and that the proportion of the longshore drift available for bar construction and bypassing has increased over time. It is a reasonable assumption that the river sediment contribution has remained quasi-constant within broad limits for the whole period from 1870.

Table 4 Annual littoral drift reductions necessary to obtain minimum inlet stability for stated flow conditions ($\Omega'/M = 150$).

Flow events	Littoral drift (m^3/year)	% of present drift	% reduction required
Tide only	1 600	1.6	98.4
Minimum flow + neap	31 100	3.1	96.9
Minimum flow + spring	45 800	4.6	95.4
Mean flow + neap	78 700	7.9	92.1
Mean flow + spring	93 400	9.3	90.7
Mean annual flood + neap	691 000	69.0	31.0
Mean annual flood + spring	706 000	70.6	29.4
Ten-year flood + neap	966 700	96.7	3.3
Ten-year flood + spring	980 000	98.0	2.0

The quantities and rates presented above are in good agreement with those presented by Mangin (1973) for the same areas, though more surveys were utilised in the present analysis.

SEDIMENT BYPASSING MODEL

Le Mehaute & Soldate (1977) have presented a mathematical model for shoreline accumulation and sand bypassing at a long groin which has found quite wide application and yielded satisfactory results to a first approximation. Although it is unnecessary to develop the model fully here, the form of the downdrift bypassing function is shown in Fig. 2. The model is developed from the general diffusion equation and it specifies a time t_1 when all sand will be trapped on the updrift side of the structure (see Fig. 2A), after which a parabolic increase in the bypass quantity will occur over time in several multiples of t_1. The quantities of sand are expressed as ratios of Q, the value bypassed at any given time, over Q_0 the "natural" net drift quantity which obtained for Carters Beach before construction of the drift barrier. As can be seen from Fig. 2C it requires time of the order of 5 t_1 to re-establish 70% of the bypass transport.

A further aspect of the model is that it deals with sand transport by bedload only. When the suspended load is introduced, the form of the relationship is altered such that the increase in bypassing after t_1 is more linear and high levels are achieved sooner (Fig. 2A).

Table 5 Accretion around Westport Harbour 1870–1979. Volumes above LWOST.

	Carters Beach		North Beach	
Period	Quantity ($m^3 \times 10^3$)	Mean rate (m^3/year $\times 10^3$)	Quantity ($m^3 \times 10^3$)	Mean rate (m^3/year $\times 10^3$)
1870–1879	1480	165	2110	235
1879–1883	—	—	1151	288
1879–1887	1180	147	—	—
1883–1892	—	—	526	58
1887–1892	647	129	—	—
1892–1901	989	110	754	84
1901–1911	695	70	—	—
1901–1921	—	—	1004	50
1911–1921	298	30	—	—
1921–1941	293	15	809	40
1941–1960	339	18	—	—
1941–1961	—	—	172	9
1961–1973	—	—	334	28
1961–1979	508	28	—	—
1973–1979	—	—	109	18
Total	6430		6970	

This model has been used to clarify the role and extent of bypassing at Westport by regarding the calculated longshore sand transport presented earlier as an upper limit to the quantities available to the entrance system and the surveyed beach accumulations as abstractions from that. Similarly, the various phases of training wall extension can be used to calculate t_1 accumulation times which should specify the periods for which beneficial reductions of the drift were obtained at each stage. It should also reveal the influence on the overall bypassing regime of each phase of construction.

In this manner, two important sets of results have been obtained. Both are shown in Fig. 3. The lower curve is derived from running the model on the training wall extension lengths at the times shown using the longshore transport formula presented earlier as initial input to Phase 1 of the construction. At Phase 2 (1916–1917) a new transport value was derived from the value for Q/Q_0 at that time and the model run repeated. Later phases of extension were treated in the same fashion. Table 6 presents the indicated t_1 times for updrift accumulation and for which beneficial reductions in drift to the bar complex could be expected.

Both the form of the curve and the t_1 values confirm that the bypassing history of the entrance has been a long-term response to the first (and longest) phase of training wall construction (t_1 = 24 years). Phase 2 (1916–1917) had an indicated t_1 time of only 2.36 years and the model shows that by 1922 any benefit had been overcome since the bypassing curve rejoins that which would have existed from Phase 1 by that date. Later phases of extension, and particularly the final phase in 1966 had a negligible effect on bar bypassing. It is noted that Phase 4 was completed for other and possibly beneficial reasons (including narrowing of the entrance to enhance scour by the outflow). Such effects cannot be evaluated from the bypassing model, but it is confirmed here that no useful drift reduction occurred as an outcome of the 1966 work.

Table 6 Extensions to Westport training wall (west) and calculated drift detention times. The lengths given under "Event" are those measured normal to the line of the littoral drift from the shoreline to the tip of the west training wall at a given time. They are thus "effective" lengths in respect of the model rather than actual construction lengths. t_1 (y) is the calculated t_1 from the model (y).

Phase	Date	Event		t_1 (y)
1	1891	West training wall out	1097 m	24.01
2	1916	West training wall out	152 m	2.36
3	1931	West training wall out	30 m	0.06
4	1966	West training wall out	46 m	0.11

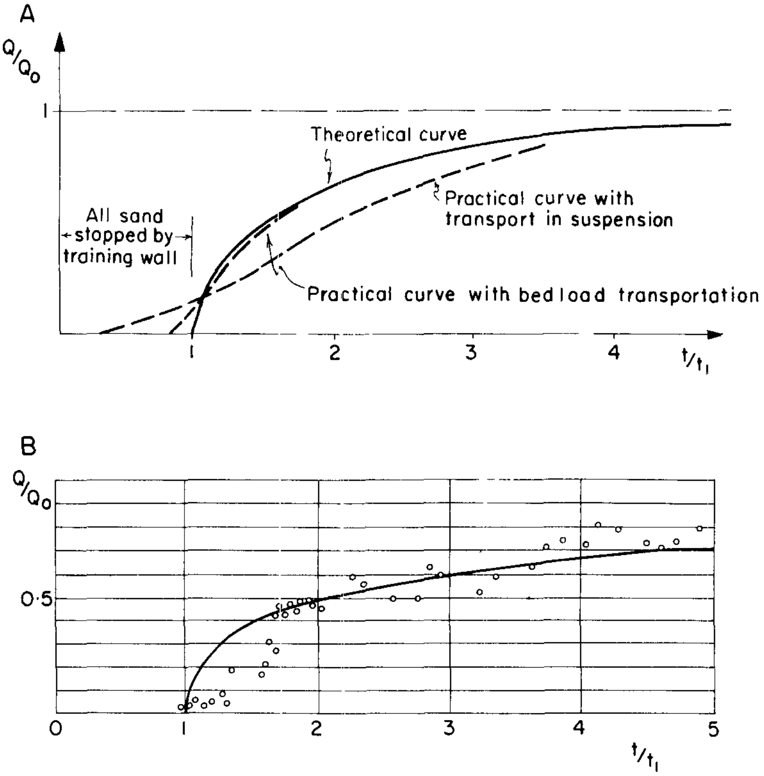

Fig. 2 Aspects of the bypassing model. A, sand bypassing a long groin as a function of time (from Le Mehaute & Brebner 1961 *in*: Le Mahaute & Soldate 1977); B, comparison between experimental and theoretical sand bypassing discharge (from Pelnard-Considere 1956, *in*: Le Mehaute & Soldate 1977); C, proportions of drift (Q/Q_0) bypassing a long groin as a function of elapsed time (t/t_l) after initial infill (after Le Mehaute & Soldate 1977).

C

t/t_l	Q/Q_0
1	0·189
1·25	0·315
1·5	0·397
2	0·498
3	0·605
4	0·665
5	0·703

Because only the first phase of extension constituted a complete interruption to the littoral drift, its associated t_l value is the only one calculated which meets the terms of the model fully. All of the other values relate to minor perturbations of the drift and are thus strictly sub-t_l events.

Another conclusion which is clear is that little improvement would be expected from further phases of training wall extension at Westport unless they were very large. In turn, that would present other problems of exposure to wave energy and possibly reduction of existing tidal scour potential in the confined channel.

The upper curve in Fig. 3 was derived by ignoring the wall extension phases and subtracting the full accumulations on Carters Beach (over 4.8 km of shore) from the calculated total drift and then expressing the differences as ratios of the total drift (Q_0). These portions of the total drift, together with the river-borne sediment load and any dredge dumpings inserted into the transport system, are regarded as the materials available for bar growth, bypassing to North Beach and progradation there. It can be seen from the diagram that a relationship of the same general form is obtained in this way. However, given stages of the curve were reached much more rapidly than predicted by the model, and at much higher values of Q/Q_0. The lines joining the data points suggest a relationship much closer to that including suspended load transport than that for bedload alone. In any event, it seems that the bypassing system, as represented by the material trapped in Carters Beach, operates in a fashion similar to that modelled so that the principles contained in the model can be applied to the bar problems with appropriate allowances for differences of scale.

In respect of the upper curve it is again important that the entrance was naturally bypassing only about 50% of the drift during the pre-construction beach accretion phase. Thereafter, training wall construction notwithstanding, the proportion of sediment being bypassed increased rapidly to a maximum of 96% by 1921 ($Q_0 = 1 \times 10^6$ m^3/year). From that year the proportion seems to have been not less than 90% so that the inshore nourishment to both bars is 0.9×10^6 m^3/year. To this must be added the river sand load (107 000 - 214 000 m^3/year) and any reworked dredge spoil from the dump ground on the outer part of the submarine delta. Most of this material is potentially available for recirculation on to North Beach.

By similar consideration of the bypassing ratio and the quantities accumulating over time, an

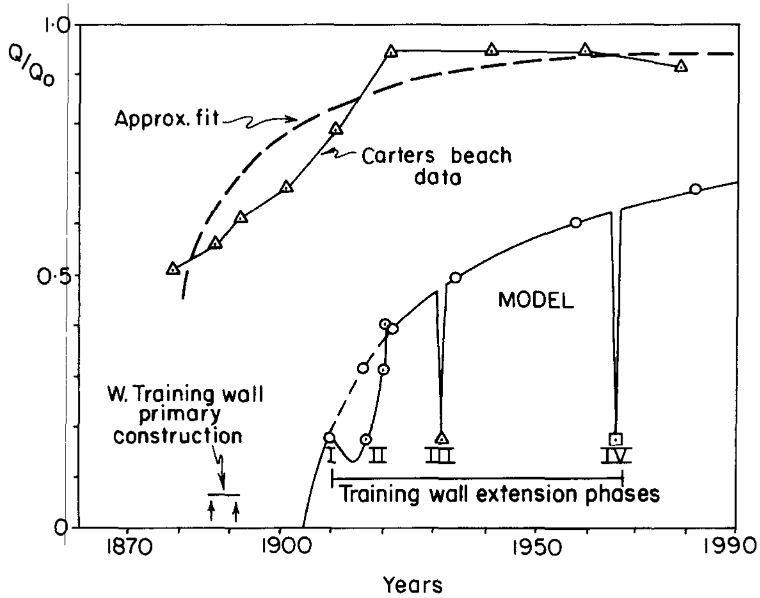

Fig. 3 Sand bypassing ratio (Carters Beach/West training wall) as a function of training wall extension history.

assessment can be made of the proportion of North Beach sand which could be directly bypassed from Carters Beach. In 1883 (pre-construction) up to 62% of North Beach sand could have been bypassed direct from Carters Beach. By 1892 when the first training wall construction phase was complete the value fell to 29%. Since then the proportions have been 16% in 1921, 13% in 1941, 3% in 1961, and only about 2% in 1979. Increasing proportions of sand have thus been circulated to the outer bar complex rather than directly to North Beach, though the total quantity fed from Carters Beach achieved a high quasi-stable level by 1921.

DISCUSSION

The analysis presented above reveals some important new aspects of the processes responsible for sedimentation and morphology of the entrance bar complex at Westport (as described by Kirk et al. 1986).

In addition to the obvious and dramatic updrift and downdrift beach accumulations, it is concluded that important consequences of the training walls have been not only to fix an "in-built" cross-entrance sediment transport potential, but also to induce *deflection* and *splitting* of the long-shore drift system.

Together with the result of the morphological and sediment studies discussed earlier and presented in Kirk et al. (1986), these findings confirm that only the inner bar, when present, *directly* bypasses sand to North Beach. The bulk of the sand reaching there does so by a circuitous route and is a mixture of river and littoral drift material and possibly dredge spoil which is recirculated over the eastern half of the delta and finally counterdrifted toward the training wall within North Beach. The term "bypassed sand" thus requires some qualification in that the western training wall and the outer bar complex provide a geometry which simultaneously has a "built-in" potential for sand transport to the east, and a deflecting effect which directs the transport to the north-east along the outer bar. Here, along with dredge spoil, it contributes first to growth of the outer bar complex, and later to recirculation off North Beach. When an inner bar is present, both direct and indirect bypassing occur. When the outer bar complex has a dispersed shape, direct bypassing at the inner bar is intense (see Kirk et al. 1986).

This interpretation explains why the outer bar occurs most frequently as a submarine extension of Carters Beach lying obliquely across the western two-thirds of the channel entrance axis line, and why high sediment loads passing the line of the west training wall contribute little sand by direct transfer to North Beach. Growth of the outer bar complex since April 1983 has been sustained by this deflected sand transport, by dredge spoil (805 000 m^3 having been dumped at the present site since 1980), and by contributions from the river. It is highly pertinent that bypassing levels have been semi-constant at more than 90% of the littoral drift volume since 1921 so that a high level of littoral drift has been available to be *split* (directly into the inner bar and indirectly deflected through the outer bar), as from April 1983 to the present; or to be *concentrated* (directly bypassed) through a single, large inner bar since that time. While the traps which are the beaches to either side of the training walls have filled almost to capacity, since the beaches have reached the outer ends of the walls; the entrance was modified, and rainfall, river discharge, and sea-states have played variations on the underlying themes from season to season and year to year.

The distribution of sediment characteristics including mineralogy, size, sorting, and particle shapes (as described in Kirk et al. 1986) is also in good agreement with the above interpretation of the sediment transport system.

Finally, all of the findings from the bypassing analysis are consistent with those based on the entrance tidal hydraulics; principally, that the Westport bar complex has its origins and primary controls in wave-induced littoral drift and that the river exerts a periodic beneficial disruptive effect on the morphology of the bar system while adding to the sediment load in transit.

CONCLUSIONS

The results and analyses presented here and in our companion paper (Kirk et al. 1986) have provided a comprehensive explanation of the Westport entrance bar system.

It has been established from a simple analysis of tidal hydraulics that Westport is pre-eminently a bar-bypassing inlet system. The tidal compartment exerts little control on bar sedimentation so that negligible improvement in navigation depths could be expected from enlargement of the compartment, a solution often advocated in the past.

It has been shown that the growth sequence of the bar complex has its origins in the in-built structural mis-orientation of the training walls with respect to refracted waves and to that extent the bars are a permanent feature of the harbour unless the net eastward littoral drift which is driven by the incomplete refraction can be modified.

The amount of littoral drift at Carters Beach has been estimated from analysis of the wave climate to be 1.0×10^6 m^3/year. This analysis and the bypassing investigation show that the primary sand drift is eastward and that about 0.9×10^6 m^3 or more pass the entrance each year. Previously, figures as high as four times this amount have been reported. River sand input to the system is perhaps 20% or less of the littoral drift input.

The outer bar or shoal is considered to be a submarine extension of Carters Beach, in effect it is downdrift growth in deeper water past the misaligned entrance walls, rather than merely being a repository for inner bar material pushed out by the river.

Floods in the river remove the inner bar and some of the material is deposited on the outer bar. It is important to note however, that floods do not remove the outer bar. Any increases in depth over the outer bar result mainly from morphological reshaping. The normal effect is for the sediment at the crest to be reworked onto the seaward face of the outer bar. A post-flood return to littoral drift control readily re-establishes a persistent morphology.

The outer bar is separated from the sometimes short-lived inner bar by a transverse channel which acts to relieve wave-induced circulation at the eastern end of Carters Beach. The outer bar is the principal mixing zone off the river mouth where littoral drift (from Carters Beach), river sediments, and probably some portion of the harbour dredge dumpings are combined for recirculation to the north.

The growth of North Beach is a lee accumulation which is a consequence of increasingly lower levels of direct sand bypassing from Carters Beach and a high, quasi-steady level of sand recirculation offshore and east of the inlet axis line.

Incomplete bypassing by splitting and deflection of the longshore transport are not thought to be contributing factors to widespread erosion of gravel shores forming the coast further north.

It is considered that the best chance of effecting any long-term improvement to the entrance channel at Westport lies in modification of the behaviour of the littoral drift regime, a problem technically achievable by several means but evaluation of which turns on political and economic as well as engineering considerations.

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REFERENCES

Bruun, P. 1978: Stability of tidal inlets — theory and engineering. Developments in geotechnical engineering 23. Amsterdam, Elsevier. 506 p.

Bruun, P.; Gerritsen, F. 1960: Stability of coastal inlets. Amsterdam, North Holland. 123 p.

Furkert, F. W. 1947: Westport harbour. *Proceedings of the Royal Society of New Zealand 76*: 373–402.

Gibb, J. G. 1978: Rates of coastal erosion and accretion in New Zealand. *New Zealand journal of marine and freshwater research 12*: 429–456.

Griffiths, G. A. 1979: High sediment yields from major rivers of the western Southern Alps, New Zealand. *Nature 282*: 61–63.

——— 1981: Some suspended sediment yields from South Island catchments, New Zealand. *Water resources bulletin 17*: 662–611.

Hallermeier, R. J. 1981: Seaward limit of significant sand transport by waves: an annual zonation for seasonal profiles. *US Coastal Engineering Research Center technical aid 81, 2.* 23 p.

Johnson, J. W.; O'Brien, M. P.; Isaacs, J. D. 1948: Graphical construction of wave refraction diagrams. *US Hydrographic Office publication 605, technical report 2.* 45 p.

Kirk, R. M.; Hastie, W. J.; Lumsden, J. L. 1986: Harbour entrance morphology and sediments at a river mouth port, Westport, New Zealand. *New Zealand journal of marine and freshwater research 20*: 689–697.

Le Mahaute, B.; Soldate, M. 1977: Mathematical modeling of shoreline evolution. *US Coastal Engineering Research Center miscellaneous report 77, 10.* 56 p.

Mangin, C. M. 1973: Coastal processes and development in the southern Karamea Bight. Unpublished MA thesis, Department of Geography, University of Canterbury, New Zealand. 112 p.

Nevins, T. H. F. 1938: Erosion at Westport aerodrome. *Proceedings of the New Zealand Institution of Engineers 24*: 487–497.

Reid, S. J.; Collen, B. 1983: Analysis of wave and wind reports from ships in the Tasman Sea and New Zealand areas. *New Zealand Meteorological Service miscellaneous publication 182.* 74 p.

Rendel, Palmer, and Tritton Consulting Engineers Limited 1946: Report on Greymouth and Westport Harbours and Point Elizabeth with notes on minor west coast harbour sites and also short reports on Nelson and Lyttelton. Unpublished report by Rendel, Palmer, and Tritton Consulting Engineers Limited, London. Copy held in Head Office, Ministry of Works and Development, P. O. Box 12041, Wellington, New Zealand.

Simpson, R. A. 1959: The West Coast harbours of the South Island of New Zealand. Paper 194, Fourth Triennial Mineral Conference, School of Mines and Metallurgy, University of Otago, Dunedin, New Zealand. 12 p.

US Coastal Engineering Research Center 1977: Shore protection manual. 3rd edition. US Coastal Engineering Research Center, Fort Belvoir, Virginia. 3 volumes.

Valentine, E. M.; Macky, G. H. 1984: Sea wave climate at Ngakawau, Westport and Carters Beach. Ministry of Works and Development Central Laboratories report 3, 84/4. 2 volumes.