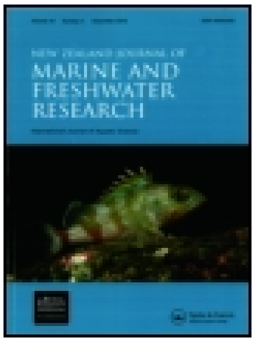

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New Zealand Journal of Marine and Freshwater Research

ISSN: 0028-8330 (Print) 1175-8805 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzm20

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To cite this article: R. H. Findlay & R. M. Kirk (1988) Post-1847 changes in the Avon-Heathcote Estuary, Christchurch: A study of the effect of urban development around a tidal estuary, New Zealand Journal of Marine and Freshwater Research, 22:1, 101-127, DOI: 10.1080/00288330.1988.9516283

To link to this article: http://dx.doi.org/10.1080/00288330.1988.9516283

New Zealand Journal of Marine and Freshwater Research, 1988, Vol. 22: 101-127
0028-8330/88/2201-0101$2.50/0

Post-1847 changes in the Avon-Heathcote Estuary, Christchurch: a study of the effect of urban development around a tidal estuary

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Abstract A detailed, previously undescribed, history of changes to the Avon-Heathcote Estuary mouth at Christchurch, New Zealand, is presented. Between 1847 and 1911 the estuary inlet was dominated by a tidal bypassing regime. Between 1911 and 1938 this changed to a mixed tidal and bar bypassing regime, with consequent erosion of the tip of the South Brighton Spit, probably permanent loss of sand from Sumner Beach, and increased vulnerability to erosion of properties in the suburb of Redcliffs. The change is thought to be related to changes in estuarine tidal compartment owing to the pre-1920–40 urbanisation of the Christchurch area. The change in estuary inlet regime, especially in the context of the post-1946 residential development of Brighton Spit, has important implications for town planning.

Keywords Avon-Heathcote Estuary; spit tip; estuary inlet changes; urban growth; inlet regime; tidal bypassing; bar bypassing

Received 3 August 1984; accepted 1 October 1987
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INTRODUCTION

Sandy spit tips, together with their associated estuary inlet channels and sub-tidal deltas, are notoriously unstable and complex systems. During the last 150 years, the inlet of the Avon-Heathcote Estuary (Fig. 1) and the distal margin of South Brighton Spit (Fig. 1) have undergone a sequence of many and complex changes, thus supporting this generalisation. Considerable importance attaches to understanding the causes, trends, and likely results of these changes because the South Brighton Spit has been used for intensive residential development. Furthermore, the geometry of the inlet plays an important role in estuarine circulation, in the safe dispersal of flood waters and other run-off from the Christchurch metropolitan area, and in the protection of parts of the urban area from ocean swell and storm surge.

Bruun & Gerritsen (1960) and Bruun (1978) examined how changes in estuary discharge and littoral drift affected the stability of tidal inlets. They concluded that, because estuarine flow and sedimentation processes are so complex, a useful approach to their study is to combine physical analysis of the inlet system with a characterisation of its controlling variables. It is then possible to make comparative analyses between the inlet under study and a wide range of others where a variety of problems, and their solutions, are understood. Broadly, these authors argue that inlet stability can be regarded as a function of the scouring power of the tidal compartment (the volume of water which enters and leaves an estuary in a given tidal cycle), and the choking ability of the littoral drift along the adjacent coast (and which is driven by wave action and wave-induced currents). A few parameters are then used to investigate this relationship over a wide range of physical conditions.

Within this approach, there has been a long-standing interest in the relationship between the volume of the tidal compartment and the cross-sectional area of the inlet channel (O'Brien 1931). The existence of such a relationship for a wide range of estuary sizes was thought to indicate a balance between throat cross-sectional area and average maximum flow velocity through the throat (Heath 1975). Because this balance was thought to be

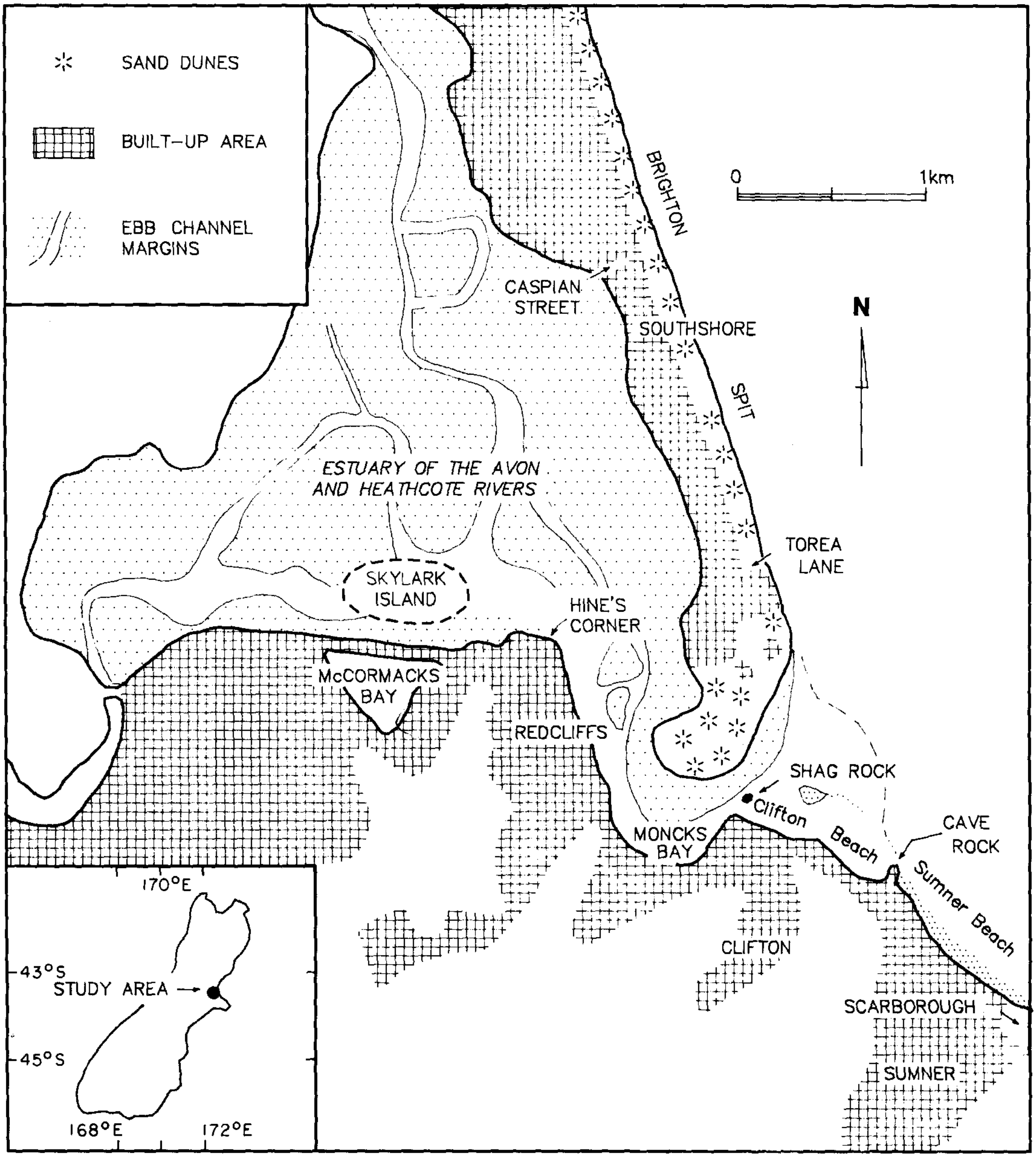


Fig. 1 Locality map; inset shows South Island, New Zealand.

dynamic, estuaries, tidal compartments, and throat areas could be expected to co-vary and thus to scour or fill to achieve a stable balance. This would suggest that deliberate or unintended human actions, affecting either or both the tidal compartment and entrance area, could well initiate compensating changes in the shape of an estuary.

This relationship is undoubtedly an over-simplification of inlet processes and of the morphological stability of inlets (for example, it takes no account of the role of waves or of littoral drift, and it presumes tidal dominance of the inlet circulation). However, the concept has been used widely, not least for the Avon-Heathcote Estuary where

Macpherson (1978) applied it to a series of historical surveys to account for the many post-1854 changes in the tip of South Brighton Spit, the inlet, and the sub-tidal delta.

Macpherson (1978) argued that the growth of Christchurch City, through its effects on the catchments of the Avon and Heathcote rivers, namely as a result of rapid run-off through the storm water drainage and sewage discharge systems, has caused changes to the estuarine tidal compartment. These changes were supposed to have led to compensating changes in the entrance cross section, the spit tip, the size of the ebb tidal delta, and the location of the principal ebb channel. It was also postulated that these changes were accompanied by large sediment gains in the estuary before 1915, by subsequent removal of this material, and then by removal of yet further substantial volumes to produce a contemporary tidal compartment much larger than the pre-urban one.

This sequence of events, detailed by Macpherson (1978) who defined them from limited historical data and explained them in terms of the tidal compartment/cross section relationship, would suggest that the morphological changes, which would have attended the net gains and losses of about three million cubic metres of sandy sediments in an estuary of 8 km² area, should have been very substantial. Such changes would be significant for the future development of Christchurch and the management of its shorelines. Further, the sequence of events proposed by Macpherson (1978) would have much wider significance: whereas it is easy to argue for processes and energy gradients which will promote estuarine sedimentation (whether from sources in the contributing catchments or the adjacent ocean areas, or from both), it is much more difficult to show — as was suggested by Macpherson (1978) — how an infilling trend might become reversed and how an estuary might achieve the energy distributions necessary for it to become a sustained net exporter of sediment to the adjacent coast.

For these reasons, further study of the Avon-Heathcote Estuary, and particularly of its inlet history, is warranted. It is our contention that recent studies, using historical observations on the history of changes at the estuary mouth (Hutchinson 1972; Millward 1975; Macpherson 1978; Kirk 1979; Kruger 1980) contain sparse historical data and thus tend to present over-simplified assessments of changes in the estuary mouth during the last 80 years.

The present study (based on Findlay 1981, 1984), made to help assessment of future changes in the estuary mouth, has shown much more historical data are available in the form of personal notes, diaries, photographs, paintings, maps, and memory than have been recorded previously. These data, still not explored fully, have an important bearing on the conclusions of previous workers, and are presented and discussed below.

Work for the present paper involved study of maps, vertical and oblique aerial photographs, researching literature including files held by public bodies and private individuals, and talking to local residents. Information from local residents was cross-checked with other sources. Sources of information are recorded in a card index held by City Engineer's Department, Christchurch City Council, consisting of 26 entries under the heading of "File", 110 entries under "Photographs and paintings", 80 entries under "Contacts", 28 entries under "Maps", 95 entries under "Literature", and 44 entries under "Storms".

THE AVON-HEATHCOTE ESTUARY

The location and form of the Avon-Heathcote Estuary, together with the ebb tidal delta complex and the adjacent ocean beaches, are shown in Fig. 1. The Avon River enters from the north-west and the Heathcote River from the south-west. According to Macpherson (1978), about 70% of the combined area of these two catchments has been urbanised since the mid 1800s.

The estuary has a triangular shape, a short inlet connection with the ocean, and is primarily enclosed by the 4 km long Brighton Spit. The southern margin of the inlet channel is formed by the volcanic rocks of Banks Peninsula and the fringes of the urban area in Moncks Bay. The estuary is small (8 km²), shallow (mean depth at HWOST is 1.4 m), and predominantly intertidal, as only about 15% of the area lies below LWOST. The ocean tidal range is 2.2 m at spring tides and 1.7 m at neap tides.

The most prominent features of the inlet are the single deep channel between Shag Rock and Brighton Spit, and a very large ebb tidal delta seaward of the entrance (Fig. 1). Wave-induced longshore transport of sand has been estimated at gross movements of up to one million cubic metres per year on the ocean beaches north of the inlet. Net transports range from zero to perhaps 10^5 m³ per year (Kirk 1979). Net transport may be either northward or southward in a given year, though there is a strongly held local belief in a substantial net southward drift toward the inlet. As will be evident later, there is no evidence of either net growth of Brighton Spit, or of the Clifton and Sumner Beaches, which would be the result from such a southerly net transport. Rather, large fluctuations have occurred in all the beaches and these were attended by changes to the ebb tidal delta. It therefore seems reasonable to regard the littoral drift near the inlet as smaller in both gross and net values and highly variable in time than is the situation for the ocean beaches further north. For this paper, the gross drift at the inlet will be approximated by the volume of the periodic fluctuations in the adjacent beaches.

Historical observations of changes

Table 1 presents a detailed chronology of the major events for the areas of beach and estuary around the inlet. Data sources used are set out in the References and Appendices.

The outlet channel

The best recognised event involving the shape of the estuary outlet is the redirection of the main ebb tide channel, from a south-east direction past Shag Rock to an outlet at Cave Rock, into its present easterly strike from Shag Rock past the toe of Brighton Spit (Fig. 1). This occurred abruptly, being noticed first on 8 June 1938 after an unusually high tide (Rule 1980), and is believed (Macpherson 1978) to have been an important factor in the subsequent extensive erosion of the recurve of Brighton Spit during 1940–49.

After a major period of erosion between 1940 and 1949, accretion at the recurve coincided with erection of a system of drum groynes and brushwood fences between 1949 and 1958. However, the dunes along the seaward part of the spit did not build out to their present position until about 1960. Since 1960, localised erosion has occurred along the Southshore beach and has endangered properties at the east end of Torea Lane (Fig. 1).

Brighton Spit

Settlement of Brighton Spit (Southshore, more-or-less south of Caspian Street, Fig. 1) started shortly after 1945, and consequently there is less information available for this region than for Sumner, which began to be settled in the 1850s.

Before urban developments commenced in the late 1940s, the region (Fig. 2) from just south of Heron Street to just south of Torea Lane was a low, swampy area separated from the sea by high sandhills. This region is marked in the 1849 "Acheron" survey as a gap in the coastline, and corresponds also to an area in Hollobon's "Ferrymead" painting (c. 1890; held by Ferrymead Museum, at Christchurch), where the artist has touched with blue the brown paint used for Brighton Spit. A local resident of Southshore, A. K. Wright, has stated that in the late 1930s this low area was burnt out by a three-day scrub fire, which may have been the extensive scrub fire photographed on the spit toe during March 1941 (photograph held by S. M. Rule of the Sumner and Redcliffs Historical Society).

In the late 1940s, the area now occupied by Rockinghorse Road (Fig. 2) consisted of swampy areas prone to flooding at high tide (A. K. Wright pers. comm. 1980). In 1947, ratepayers complained that access to Southshore was, "impossible except at low tide", and that "access to the majority of sections [in Southshore] is impossible for the majority of winter months except at low tide along the edge of the estuary" (Southshore Ratepayers' Association Records; archivist A. K. Wright). This implies strongly that the sea was flooding the Caspian Street region (Fig. 2).

A local resident of Southshore, A. Ell (pers. comm. 1980) recalled being told in 1949, by a then 75-year-old local inhabitant that, at the turn of the century, there existed at Caspian Street an outlet to the sea. Alledgedly, it was deep enough to require crossing by a small boat kept moored on one bank of the channel. A. Ell recalled also that in 1949 he found a layer of peat about 1 m below the land surface at Caspian Street. Similarly, A. K. Wright (pers. comm. 1980) found peat under a sand layer in Rockinghorse Road. A resident of Ebbtide Street (Fig. 2), Southshore, D. Jarden (pers. comm. 1980) stated that in the late 1930s the Ebbtide Street region was at sea level, and that fill to a depth of 1.5–2 m was required before building at 11 Ebbtide Street. In 1958, A. K. Wright (pers. comm. 1980) filled a marshy area occupying six sections (1–1.5 ha) before building at the intersection of Caspian Street and Estuary Road (Fig. 2).

Although this would appear to indicate that the Caspian Street area was originally a low area, and possibly was once occupied by an outlet to the sea, such an outlet is not shown on the 1847–49 Lands and Survey Black Map, on the 1879 Lands and Survey map and accompanying surveyor's notebooks, or in the 1904 Lyttleton Harbour Board Survey. Furthermore, neither Hollobon's "Ferrymead" painting (c. 1890) from Castle Rock, nor Madden's painting (see Fig. 3) (c. 1890) from Moncks Spur show any evidence of an outlet in the Caspian Street region, although the latter does show a deep bay here on the estuary side and a large blow-out on the seaward side. A local resident, J. N. Knight (pers. comm. 1981) has indicated that, between 1940 and 1945, the Army bulldozed flat the sandhills and stripped the vegetation in the Caspian Street region to set up a defensive position. This work may have lowered the land surface so that after 1945 the Caspian Street region was prone to extensive flooding by sea and estuary waters.

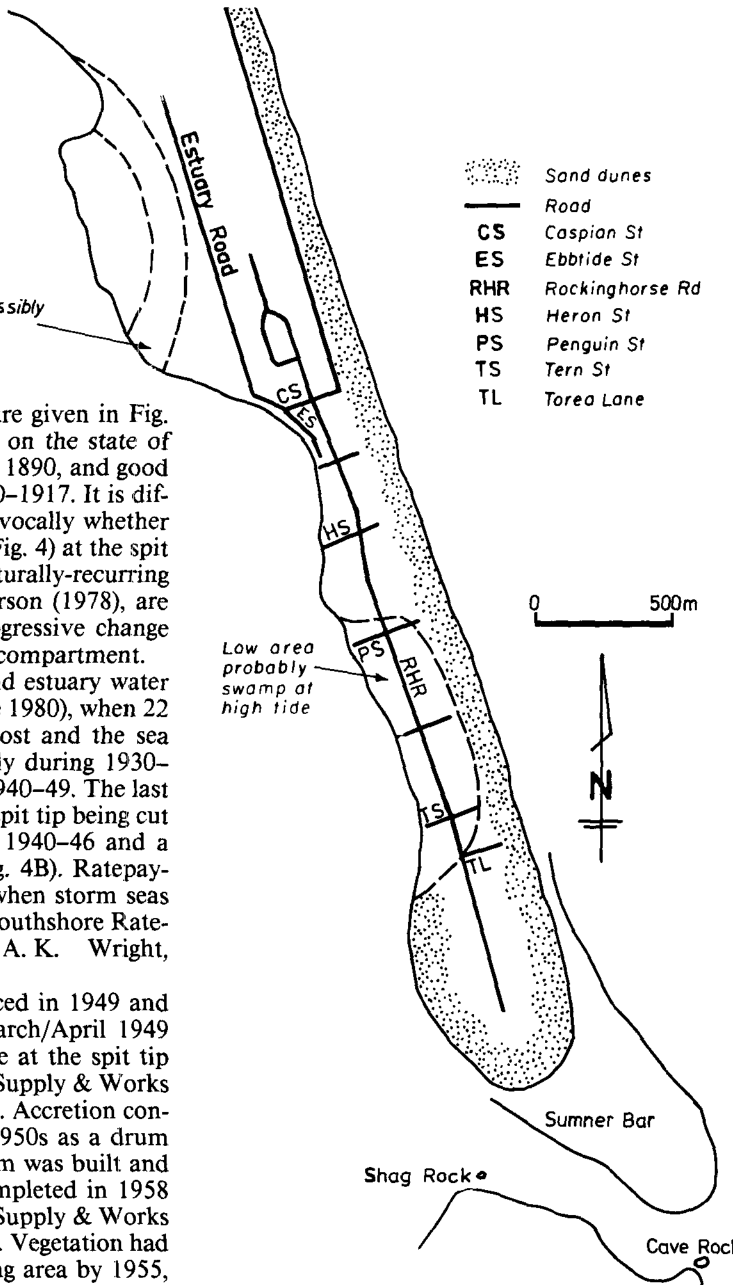


Fig. 2 Low areas in Brighton Spit in the 1920s. Roads built after 1947 added for reference.

Erosion at spit tip

Details of changes at the spit tip are given in Fig. 4. As yet, there is no information on the state of the Southshore beach before about 1890, and good data are lacking for the period 1890–1917. It is difficult therefore to establish unequivocally whether or not changes recorded (Table 1; Fig. 4) at the spit tip are part of a sequence of naturally-recurring events, or, as asserted by Macpherson (1978), are part of a unique, but orderly, progressive change resulting from an increasing tidal compartment.

Erosion of the spit tip by sea and estuary water was recorded during 1918–22 (Rule 1980), when 22 acres (Pearse 1950: fig. 51) were lost and the sea breached the sandhills, sporadically during 1930–37 (Rule 1980), and again during 1940–49. The last phase was the most extensive, the spit tip being cut back northward by 350 m during 1940–46 and a further 150 m during 1946–49 (Fig. 4B). Ratepayers became alarmed first in 1948 when storm seas breached the inner line of dunes (Southshore Ratepayers' Association Records: A. K. Wright, archivist).

An accretionary phase commenced in 1949 and coincided with the erection in March/April 1949 of an experimental sandbag groyne at the spit tip (Christchurch City Council Water Supply & Works Committee minutes, 16 May 1949). Accretion continued during the early and mid 1950s as a drum groyne and brushwood fence system was built and extended, the final work being completed in 1958 (Christchurch City Council Water Supply & Works Committee minutes, 16 April 1958). Vegetation had become established on the accreting area by 1955, and the region had become completely vegetated by 1965.

Although in the mid 1950s the spit tip was becoming consolidated, in the Torea Lane region the foredunes' seaward scarp lay west (i.e., on the present landward side) of the present three houses at the lane's eastern end (Morris 1980). By 1960, the spit in the Tern Street region (Fig. 2) had reached its maximum breadth (Scott 1980), although erosion between Tern and Plover Streets was reported in 1962 (Christchurch City Council Water Supply & Works Committee report 1962). In 1963 the first of the three houses at the east end of Torea Lane was built, and in 1964 the owner sought and was granted permission to erect sea protection on the seaward side of his property (Christchurch City Council Water Supply and Works Committee report, 4 April 1964).

In spite of general progradation of the spit toe during 1964–77 (Kirk 1979), erosion, followed by rapid recovery, recurred at Torea Lane in 1968 (Southshore Ratepayers' Association: A. K. Wright, archivist).

Fig. 3 (opposite page) Photograph, courtesy of the Turnbull Museum, of a painting by J. M. Madden, c. 1890, showing the estuary, Brighton Spit, an inlet in the Caspian Street area, and a possible recurve. The vantage point would be the hill at the present suburb of Clifton (see Fig. 1).

Table 1 *(This page and three following pages)* Chronology of events in and near the Avon-Heathcote Estuary, established from historical data (from Findlay 1984).

	SHAG ROCK - CAVE ROCK			SCARBOROUGH
	1849		1849	Large lagoon at Scarborough Reserve.
EROSION	1851	Sharp scarp on seaward face of sand-dunes along Clifton Beach.		
	1864	Dunes near Cave Rock, Wreck of S.S. Augusta.		
	1868	Beach cut back to road in front of Day's Hotel (Clifton).		
	1871	Beach cut back to road in front of Day's Hotel.		
	1874	No dunes on Clifton Beach.		
	1882	No dunes on Clifton Beach near Cave Rock.	1882	Dunes along main Sumner Beach show no erosive scarps.
	1884	Sumner Pier built. Small stone wall built here covered by sand in 1914.		
	1886	Telephone poles on beach near site of tramway bridge.		
	1888	Tramway bridge built.		
	1890	No accurate date: no dunes on Clifton Beach.		
	1896	Small dunes near Cave Rock.		
	1900	No vegetation between Gollans Pt. and Shag Rock. Date uncertain: sand exposed at low tide at end of Sumner Pier.		
	1903		1903	Erosion of main Sumner Beach.
	1905	At high tide water comes up to road between Gollans Pt and Shag Rock.		
ACCRETION	1907	Date uncertain: dunes & deep sand east of tramway		
	1908	bridge - dune scarp cut back giving 1-1½ cliff.	1908	Dunes cut back.
	1909	Silting at Cave Rock. Lifeboat moved to Scarborough.	1909	Lifeboat moved from Cave Rock to Scarborough end.
	1910	Beacon Rock accessible at low tide.		
	1913	Lifesaving Pavilion built: sandhills graded: sea wall built along Clifton Beach but almost destroyed by heavy seas.		
	1914	No dunes on Clifton Beach in Cave Rock area. Stone wall built in 1884 now buried in sand.		
	1915	Causeway between Gollans Pt and Shag Rock started.	1915	Three week period of erosion forms sharp scarp.
	1916		1916	Erosion near Bell's Baths during last two years.
	1917		1917	Erosion at Scarborough Boat Harbour.
ACCRETION	1918		1918	Storm damage at Boat Harbour.
	1919	No dunes on Clifton side of Cave Rock.		
	1920	Silting along Clifton Esplanade: Mussel Rock accessible.		
	1921	Beacon Rock accessible, pier silted up at low water: no vegetation on Clifton Beach.	1921	Storm damage at Bell's Bath; sea through dunes on main Sumner Beach.
	1922	Sand building up under pier.	1922	Sand builds up on main Sumner Beach; storm damage at Bell's Baths; Bell's Baths tending to silt up.
EROSION	1923	Walls built at Cave Rock: some scour of sand in storm.		
	1924	Sandhills near Shag Rock cut back: followed by rebuilding. Heavy scour near pier.	1924	Scouring at Bell's Baths.
	1925	Scouring at tramway bridge.	1925	Erosion at high tides.
	1926	Scour at tea rooms near Cave Rock.		
ACCRETION	1927	Sand build up near tea rooms.	1927	June: storm damage of sandhills which had been building up for many months.
	1928	Pier surrounded by sand, channel shifts 50m east. Murchison earthquake. Lagoon forming on Clifton Beach.		
	1929		1929	Erosion of Sumner Beach, sand deposited near pier.
	1930	Mussel and Beacon Rocks accessible.	1930	Erosion at Scarborough end.
	1931	Minor erosion near pier.	1931	Sea wall built at Scarborough end.
	1932	Minor erosion near Cave Rock.	1932	Sand builds up over Scarborough wall.
	1933	Minor erosion at Clifton, but accretion at Cave Rock.		
	1934	5600m^3 of sand used in backfilling behind Gollans Pt-Shag Rock causeway.	1934	Lifeboat moved to Shag Rock because of silting at Scarborough.
	1936	Sand builds up at Cave Rock: outer rocks now buried.		
	1937		1937	S.S. Muriel aground. Dunes between walls at Cave Rock and Sumner. Temporary extension of Sumner Bar well past Cave Rock.

(These columns continued on p. 108)

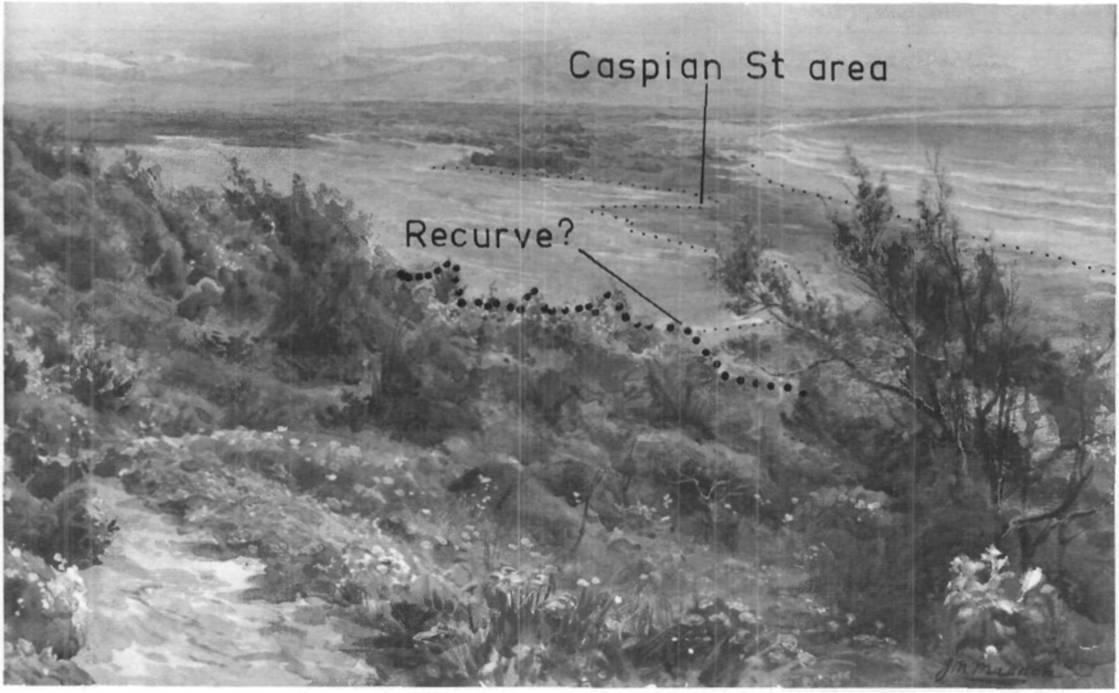


Table 1 *(Continued).*

		BRIGHTON SPIT		ESTUARY MOUTH / MONCKS BAY
	1890-	(Date approx.) High sandhills at spit-tip.		
	1906-		1906-	Island near "Cutting" has fenced enclosure and is used for grazing (Skylark Island).
	1907-		1907-	Tram causeway built across McCormacks Bay.
	1909-	Herring Bay wall built using sand from dunes and clay from river.		
	1910-	Mid-tide: shallow channel in Sumner Bay along present outlet.		
	1911-		1911-	Artesian well sunk on Skylark Island.
	1914-		1914-	Rapid erosion of Skylark Island commences.
EROSION	1916-	Low-tide: channel in Sumner Bar along present outlet.	1916-	Flooding at Redcliffs. Skylark Island covered at high tide.
	1917-	Sandhills at spit-toe cut back.	1917-	Flooding at Redcliffs.
	1918-	Sea floods Tern St from Estuary: flood extends to Rockinghorse Rd: erosion of spit-toe continues.		
	1919-	Caspian St area flooded: continued cut back of spit-toe.	1919-	Flooding at Redcliffs. Skylark still visible.
	1920-	Largest sandhills at spit-toe now lost.	1920-	Skylark Island reduced to mudflats: artesian well in deep water. Beach next to main road becomes sandy.
	1921-	Erosion on both western and eastern side of spit-toe.	1921-	Flooding at Redcliffs and Pleasant Pt. Estuary channel cuts into spit; sand bank forms in estuary mouth.
	1922-	Sea cuts through sandhills; spit-toe develops.	1922-	
ACCRETION	1923-	Spit extends south: implies spit hook is still growing.	1923-	No flooding recorded at Redcliffs.
	1924-		1924-	
	1925-		1925-	Flooding at Redcliffs. Northern channel closed; only two navigable streams in Moncks Bay.
	1927-	Spit-toe rebuilding.		
	1928-		1928-	Low-tide flow through south side Moncks Bay.
	1929-		1929-	Erosion on Moncks Bay side of middle channel (implies three channels through Moncks Bay)
EROSION	1930-	Sumner Bar now a major sand bank. Erosion of spit-toe recommences.	1930-	Main channel previously on north side Moncks Bay, against spit, moves into south side Moncks Bay.
	1932-	Erosion of spit-toe.	1932-	Flooding at Redcliffs.
	1933-	Erosion of spit-toe. Cut back approx. 400 m.	1933-	Beachville sea wall completed.
	1934-	Erosion of spit-toe.		

(These columns continued on p. 109)

Table 1 *(Continued from p. 106).*

SHAG ROCK - CAVE ROCK			SCARBOROUGH		
OUTLET CHANGE →	1938-	===================================		1938-	===================================
ACCRETION	1940-		EROSION	1940-	Beach cusps (Short 1978) visible in air photos.
	1941-			1941-	Anti-tank ditch dug, dunes removed from between Sumner and Scarborough walls.
	1943-			1943-	Scrub fences erected between Sumner and Scarborough walls.
	1945-			1945-	Anti-tank ditch filled; no dunes present.
	1946-	Area behind tramway pier filled. Vegetated dunes on beach.		1946-	Erosion in heavy storm in July, beach rebuilds in quiet conditions.
	1948-	Rubble dumped on Clifton Beach. Vegetated dunes present.		1948-	Heavy scouring all along main Sumner Beach.
	1949-	Sand deposited at Cave Rock; brought in by sea from Sumner Beach.		1949-	Continued scour at Scarborough end; deposition at Cave Rock.
	1951-	Vegetation between Clifton Bay and Shag Rock.		1951-	Sea wall scoured to its foot.
EROSION	1952-	Water deepening between Cave and Shag Rocks. Rubble lost by attrition, more dumped.			
	1954-	Clifton Beach vegetated; sandhills lost in storms during 1954.		1954-	Destruction of part of Sumner sea wall and flooding (March).
	1957-	Flooding at high tide on March 15 in Clifton Bay.			
	1958-			1958-	Wall built along main Sumner Beach.
	1959-			1959-	Sea splashing over wall at Scarborough end.
	1960-	No dunes on Clifton Beach.			
	1961-	No dunes on Clifton Beach.			
	1964-	Lifeboat moved to Scarborough end because of silting.			
ACCRETION	1965-	No vegetation on Clifton Beach.			
	1967-	Vegetation appearing on Clifton Beach.			Rubble in front of sea wall.
	1968-	Small vegetated dunes on Clifton Beach.			
	1969-	1m groyne built to assist sand build: sand drifting inland.			
	1972-	Low vegetated dunes on Clifton Beach, but none between Gollans Pt and Shag Rock. Dunes persist till 1978.			
	1978-	Storm erodes sandhills.			
	1980-	Dunes lost from Clifton Beach; erosion at Surf Club.		1980-	Lifeboat at Scarborough end silting (beginning of accretionary phase?).

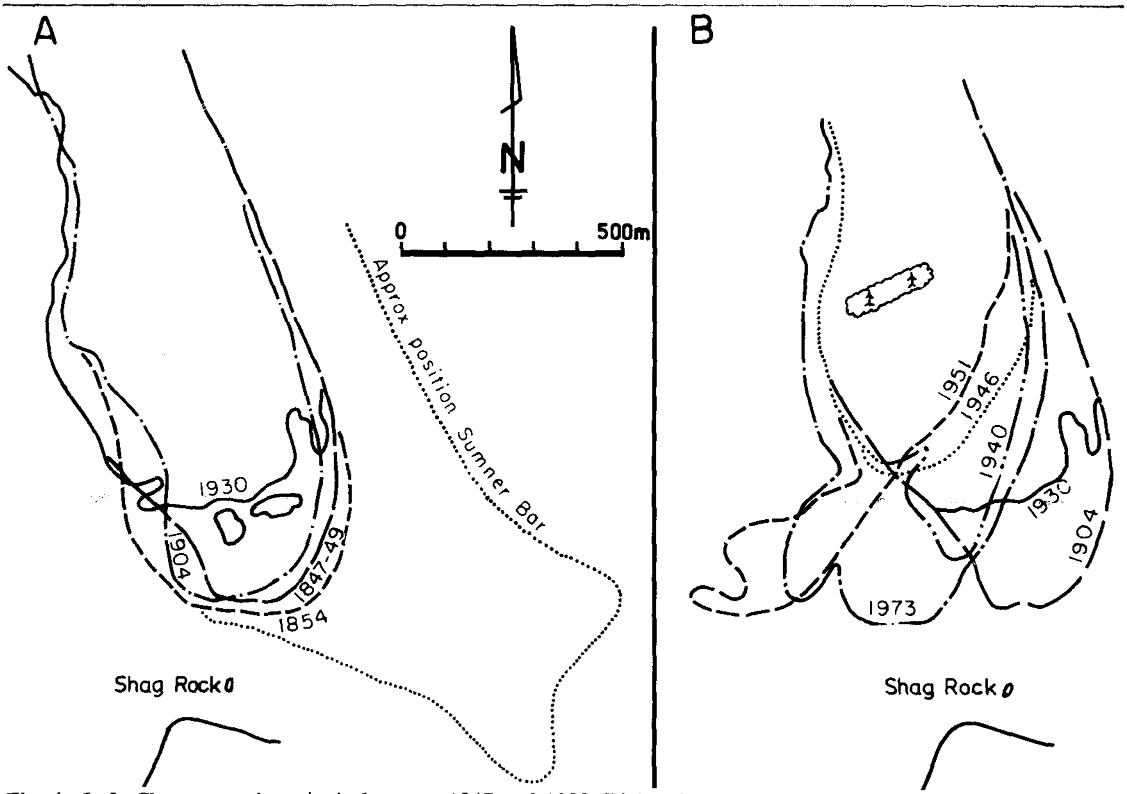


Fig. 4 Left: Changes to the spit tip between 1847 and 1930. Right: changes to the spit tip between 1904 and 1973.

Table 1 *(Continued from p. 107).*

		BRIGHTON SPIT		ESTUARY MOUTH / MONCKS BAY
OUTLET CHANGE →	1938	*June-August: present outlet to Estuary forms.* ========	1938	*June-August: present outlet to Estuary forms.* Erosion at Redcliffs.
EROSION	1940	Waimakariri mouth redirected. Spit hook starts to form.	1940	Ebb-delta channel discharges due east.
	1941			
	1942	Widespread scrub-fire in March.		
	1943	Spit occupied by Home Guard and Territorial Units.	1943	Erosion at Redcliffs.
	1944	Caspian area bulldozed. Defensive positions built.	1944	Beachville sea-wall raised.
	1945			
	1946	Extensive flooding at south end of Estuary Road.	1946	Ebb-delta channel discharges due east.
	1948	Spit-toe cut-back; sea through sandhills, but *local accretion noted.*	1948	Mouth 800 m wide.
	1949	Groynes & 2 brush fences built at spit-toe. Caspian to Godwit St. filled with sand from beach.		
ACCRETION	*1950*	Sand bank forming at *1948* breach.		
	1951	Extensive spit hook: sand building up round groynes.	1951	Ebb-delta channel discharges north.
	1952	Sand builds up round groynes. Flooding in Caspian St: Rockinghorse Rd built up to prevent flooding.		
	1953	Rockinghorse Rd flooded 25th May.		
	1954		1954	Ebb-delta channel discharges east. Erosion at Redcliffs.
	1955	Foredune scarp at back of properties at east end Torea Lane.	1955	Ebb-delta channel discharges east.
	1957		1957	Erosion at Redcliffs.
	1958	Sections at Estuary Rd-Caspian St intersection *filled.*		
	1959		1959	Severe scouring at Redcliffs.
	1960	Tsunami; minor alteration to ebb-delta.	1960	Ebb-delta channel discharges NNE-NE.
	1961		*1961*	*Erosion at Redcliffs.*
	1963	First house built at east end of Torea Lane. Spit at Tern St. maximum width.		
LOCAL EROSION	1964	Drum protection provided for houses at end of Torea Lane by owners.		
	1965		1965	Ebb-delta channel discharges east.
	1968	More erosion at Torea Lane; recovery rapid. Ebbtide St. flooded 13.4.1958.	1968	Mortons Jetty demolished.
	1973		1973	Ebb-delta channel discharges south.
	1978	Renewed erosion at Torea Lane.		
	1979	Erosion at Torea Lane.		
	1980	Erosion at Torea Lane.		
	1981	Sand builds up at Torea Lane. Localised erosion at spit-toe.		

Erosion of the spit tip recommenced in 1977 (Kirk 1979) and extended well north past Torea Lane (1977–80). Since late 1980 a slow accretional recovery has occurred, though it has been interrupted episodically by storm-wave induced erosion (for example, during strong easterly winds and waves on 12–15 June 1981).

Spit hook developments

It is accepted generally (see Kirk 1979) that the present hook-shaped spit tip developed progressively between the 1920s and mid 1950s. Although small spit recurves were observed during each of the erosive phases (1918–22; 1930–37; 1940–49), and Madden's painting (Fig. 3) suggests a vegetated recurve in the 1890s, the present recurve did not form until after 1949.

During the 1918–22 erosion event, the small recurve then formed seems to have had little effect on the direction of the estuary outlet. However, at times during the 1930–37 event, a recurve temporarily blocked the northern channel in Moncks Bay (Rule 1980). At the end of the 1940–49 erosion phase, groynes established during 1949–53 assisted greatly the consolidation of the 1949 spit tip (Pearse 1950), thus confining the main estuary outlet channel to the southern side of Moncks Bay.

Ebb delta changes

Shape and position of the ebb delta can be determined with reasonable accuracy from aerial photographs by the position of the most seaward line of breakers around the estuary outlet, and also by examination of soundings on marine charts. Full details of ebb delta changes are illustrated as appendices to Rule (1980); major changes to the ebb delta are summarised in Fig. 5 (see also Fig. 6).

Changes during 1847–1938: during this period, the main ebb tide channel discharged into the sea in the vicinity of Cave Rock, and a large sandbank, exposed at low tide (the "Sumner Bar"), extended south across the present outlet to near Cave Rock. Detailed records of changes in Sumner Bar before 1916 are as yet unknown; observations contained in Rule (1980), and comments of old residents, indicate that in the 1920s and 1930s the channels across the Bar could change daily.

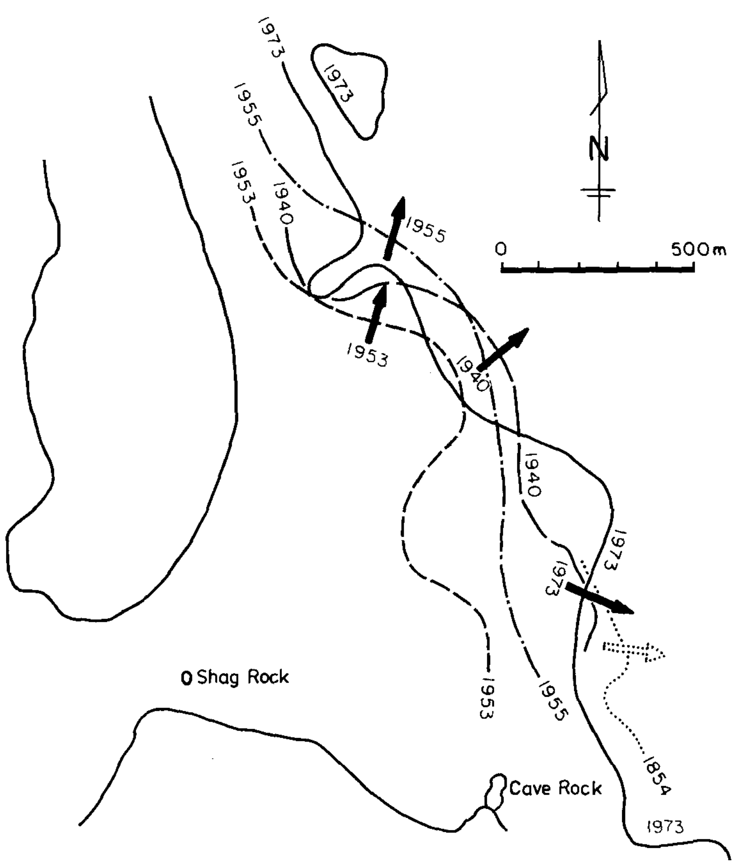


Fig. 5 Extreme positions of the ebb delta; arrows show outflow of respective ebb tide channels.

It is noteworthy from examination of the 1854 "Pandora" survey, and photographs taken between 1900 and 1940, that in 1854, and between 1904 (Figs. 7, 8, 9, 10, 11) and 1937, a shallow outlet crossed the Bar more or less along the line of the present channel. A photograph, held by Canterbury Museum, taken from Kinsey's house (Kinsey Road) in 1910 during a garden party for Capt. R. F. Scott, shows this subsidiary outlet to be partly dry at low tide, whereas photographs dated 1917 (Fig. 9) suggest it was open at low tide. Although the channel was blocked in 1930 (Rule 1980), oblique aerial photographs by V. C. Browne (Fig. 11) show that, at some time in 1937, it was open at mid to low tide.

During 1929, minor changes occurred to the main ebb tide channel (Rule 1980). Sand covered Sumner Pier and blocked the channel that curved round Shag Rock into Clifton Bay, forming a deep lagoon that persisted into the mid 1930s. After 1930, the main outlet flowed straight from Shag Rock past Cave Rock; in 1931, and again in 1937, Sumner Bar grew south, seaward of Scarborough Beach (Rule 1980), until it extended as far as 800 m south of Cave Rock.

Changes during 1938 - Present: the change in channel direction, from a south-east strike past Shag Rock to the present easterly strike, was observed first on 8 June 1938 following a high tide which was not accompanied by a storm (Rule 1980). The new channel course, which forms the present main outlet, followed that of the subsidiary described above.

Ebb delta changes since 1938 have involved changes in its area and in direction of outlet of the ebb tide channel (Fig. 5). In 1951–53 the main channel outlet was discharging sediment northward along the shore of Brighton Spit; in 1973 the outlet was discharging well to the south, and the delta margin had migrated south close to the 1854 margin (Fig. 5). In general, the delta margin has oscillated around a mean position approximating the 1940 position.

Changes in Moncks Bay

Only four maps (1847–49 Black Maps; 1849 "Acheron" Survey; 1858 Red Maps; 1904 Lyttleton Harbour Board Map) show channels in Moncks Bay for the period 1847–1910. There is disagreement

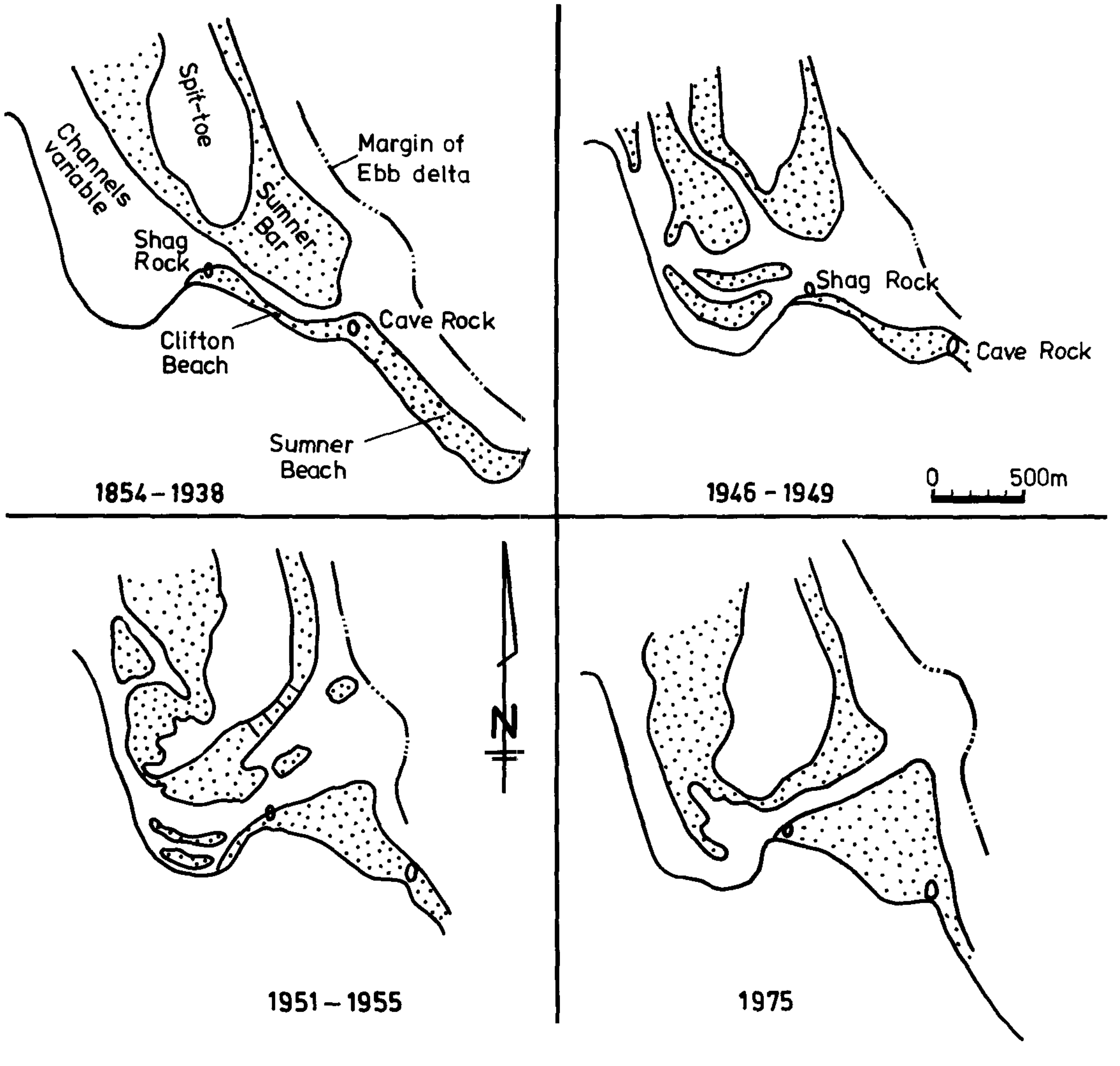


Fig. 6 Summary of changes to the estuary mouth between 1854 and 1978. Adapted from Macpherson (1978).

between the 1847–49 Black Maps and the 1849 "Acheron" Survey in number of estuary channels, and also in shape of coastline and orientation of Brighton Spit. We assume that the Lands & Survey Black Maps were surveyed accurately and prefer their information. Although the 1847–49 Black Maps and 1904 Lyttleton Harbour Board chart show a wide northern channel and a narrower southern channel in Moncks Bay, by 1916–17 a third channel (Fig. 8) had disrupted the large, possibly partly-vegetated sandbank extending from Hine's corner (Fig. 12A) to Moncks Bay.

It has been supposed generally (Macpherson 1978; Kirk 1979; Kruger 1980) that between the mid 1920s and mid 1950s the main channel migrated southwards progressively into Moncks Bay. This is a simplification (see Fig. 13) and although the northernmost of the three channels in the 1920 Lyttleton Harbour Board map (Fig. 13C) was closed temporarily in 1934 and 1936, in both 1940 (Fig. 13C and 14) and 1946 (Fig. 14 and 15) it remained an important outlet. Vertical (Fig. 15) and oblique aerial photographs (Fig. 17) show that, between 1946 and 1948, the main flow in Moncks Bay was transferred to a central channel approximately in the position of the middle channel shown in the 1920 Lyttleton Harbour Board chart. By 1951 (Fig. 16), the growing recurve had blocked this

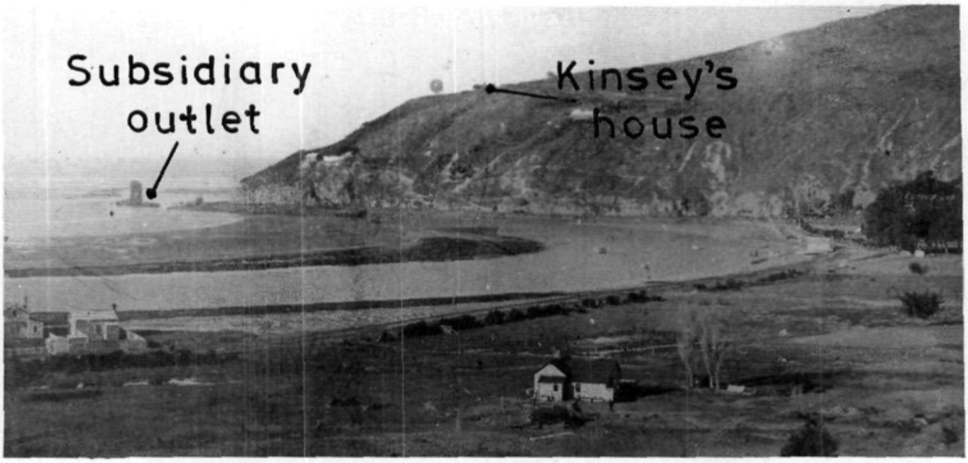


Fig. 7 View across Moncks Bay to Shag Rock c. 1900–04. Note low tide outlet across Sumner Bar. The house in the foreground was moved to make way for Wakatu Street; Kinsey's House is above Clifton Heights. Courtesy of Sumner and Redcliffs Historical Society.

channel also, and since then the estuary has drained solely through the present channel on the southern side of Moncks Bay.

Although Macpherson (1978: fig. 5) indicates that the present estuary outlet developed as the main estuary flow migrated southwards into Moncks Bay, as outlined above, this is not so; rather the present ebb tide outlet was cut in 1938 along an old, and apparently persistent, subsidiary channel across Sumner Bar, whereas the main flow through Moncks Bay was not transferred, apparently permanently, to the southern channel until 1947 at the earliest.

Disappearance of Skylark Island

Before 1920 Skylark Island, known also to some local residents as Rat Island, was a reasonably large, vegetated, grazed, and supposedly subdivided flat lying off the eastern end of McCormacks Bay (Fig. 12B). An artesian well was established there by Christchurch City Council in 1911. Erosion of Skylark Island began immediately after construction of the McCormacks Bay tram causeway (Fig. 12B) in 1907, and by 1922 Skylark Island had been reduced to mudflats covered at high tide, and the artesian well stood in a deep-water channel (Rule 1980).

Clifton and Sumner Beaches

As the Sumner settlement had become well established by 1880, these two beaches (Fig. 1) have been important recreational areas for at least 100 years and have long been subjects for painters and photographers. Most photographs available are undated snapshots and postcards, but can be dated with fair precision according to construction and demolition of prominent landmarks (see Appendix 1). The earliest known photograph is that of the wreck of S. S. *Augusta* at Cave Rock (1864); the earliest painting yet known is a lithograph of Cave Rock, by W. Holmes in 1851.

Both beaches have been modified by construction of sea walls (Fig. 12C) since at least 1867 (de Thier 1976). Although it is common (Kirk 1979) that sea wall construction hinders later build-up of sand, the 1930–31 wall at Scarborough was covered in sand within two years of its construction (Rule 1980). Similarly, sometimes extensive sand dunes have developed on Clifton Beach despite the presence of sea walls in this region since at least 1867.

Detailed information on events involving these beaches is presented and interpreted in Table 1. These data emphasise that littoral drift, especially in the late 1920s and early 1930s, could move large quantities of sand very rapidly. In one episode, sand movements caused the position of the inlet mouth to be displaced by 150 m to the east (1928, Table 1), filled the inlet channel, then about 8–9 m deep, and also covered a pier built about 3–5 m above mean sea level. This change occurred apparently irrespective of events further north where (1930) the spit tip was eroding. Table 1 shows also that there seem to have been alternating periods of erosion and accretion on Clifton Beach, and that Sumner Beach has not rebuilt to its former extent since 1940–45, when the Army build extensive defensive positions on it.

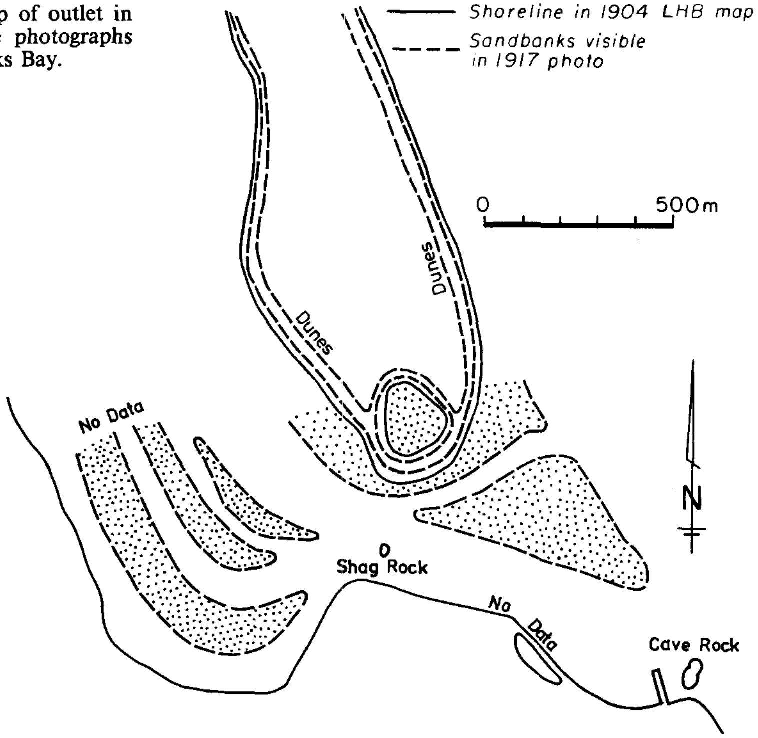


Fig. 8 Sketch map of outlet in 1917 from oblique photographs taken above Moncks Bay.

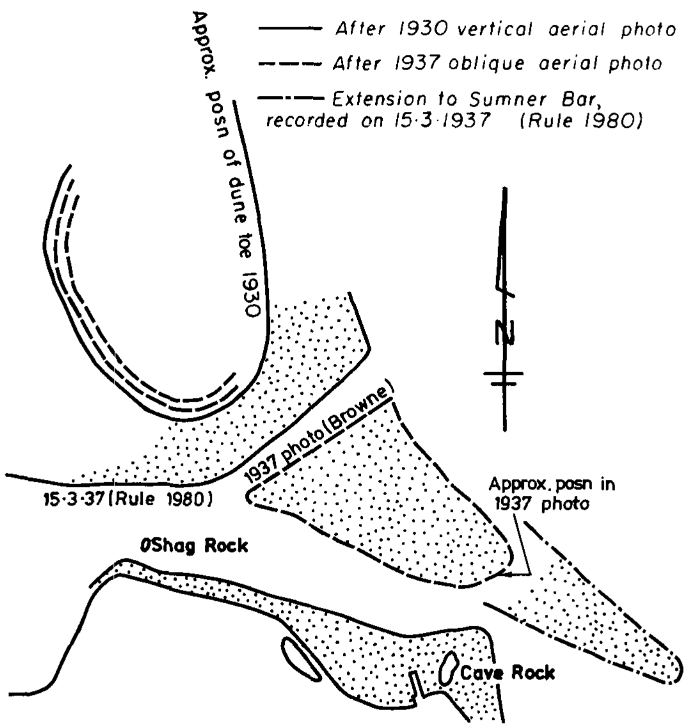


Fig. 9 Variations in Sumner Bar during 1935–37. From oblique aerial photographs and data from G. F. Allen's scrapbooks, held by Sumner and Redcliffs Historical Society, and compiled in Rule (1980).

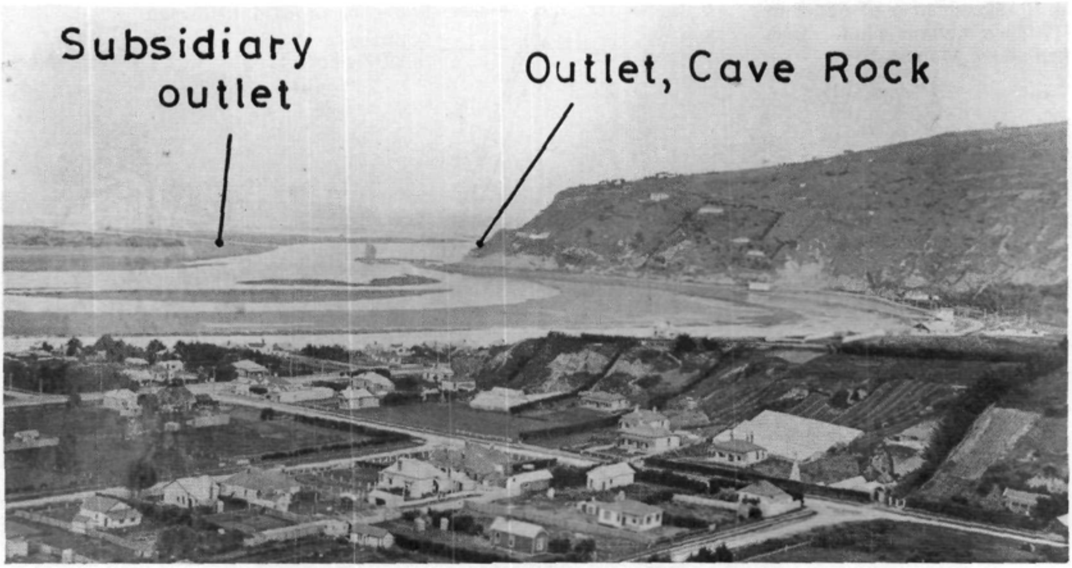


Fig. 10 View across Moncks Bay on 22 June 1917. Note erosion of sandbank visible in Fig. 7, and persistence of the subsidiary outlet across Sumner Bar. Courtesy of the Sumner and Redcliffs Historical Society.

DISCUSSION

Changes in tidal compartment

Heath (1975) showed that water tends to flow at an average maximum rate of 1.14 m/s through a supposedly stable estuarine inlet, that the cross-sectional area of the inlet covaries with the tidal compartment to accommodate this rate of flow, and that there is a simple relationship between inlet cross-sectional area and tidal compartment for a wide range of estuary sizes in New Zealand (the so-called "Furkert-Heath relationship' of Macpherson 1978, which extends the work of O'Brien 1931).

Macpherson, in his determination of the tidal compartment of the Avon-Heathcote Estuary for eleven dates between 1854 and 1974 (Fig. 18), used this relationship to predict the tidal compartments for 1854, 1874, and 1904 and also to compare predicted 1920 and 1962 values with the results of surveys by Christchurch Drainage Board and Lyttleton Harbour Board in 1920 and 1962 (see Table 2).

Although it is dangerous to use any covariant relationship to make direct predictions, our purpose below is to re-evaluate those that were made

Table 2 Tidal compartment measures for Avon-Heathcote Estuary (from Macpherson 1978). "Predicted" values derived from Furkert-Heath relationship; "direct measurement" values derived from systematic surveys of the Estuary. Note close agreement between predicted and directly-measured values for 1920 and 1962.

	Survey	Depth at Shag Rock (m)	Width at mid-tide (m)	Adjusted cross-sectional area (m^2)	Tidal compartment ($\times 10^6$ m^3)
Pandora	1854	9.14	91.4	460	7.74
Whateley-Elliot	1874	5.98	70.1	305	5.14
McIntyre & Lewis	1904	5.98	118.87	378	6.534
Joshua Little	1911	–	–	–	4.826 predicted
L.H.B./C.D.B.	1920	8.84	100.58	489	8.785 direct measurement
		–	–	–	8.184 predicted
Bruce	1953	–	–	–	10.195 direct measurement
Royds & Sutherland	1962	8.53	118.87	557	10.805 direct measurement
		–	–	–	9.14 predicted
C.D.B.	1975/77	–	–	–	10.9285 direct measurement

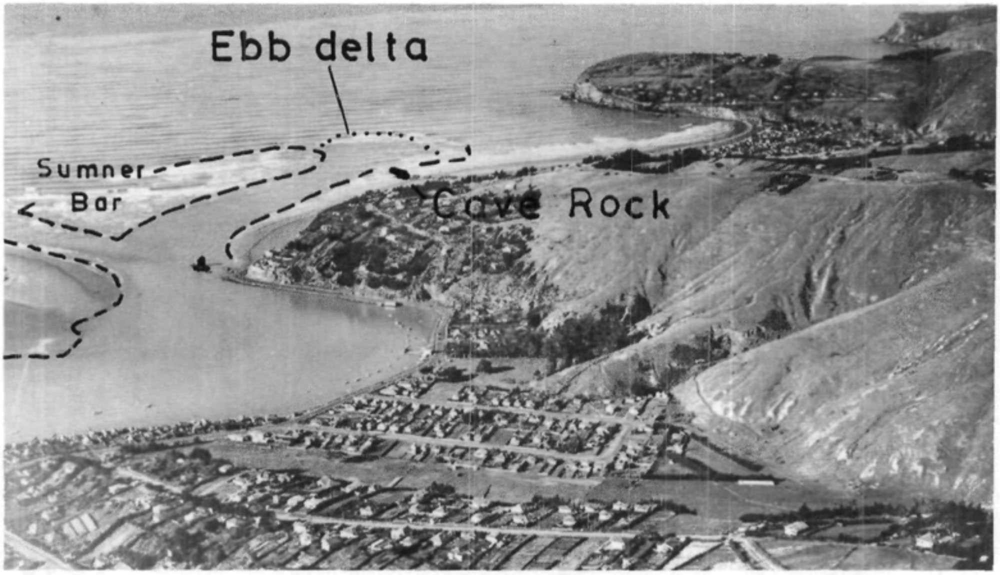


Fig. 11 Estuary outlet in 1937. Note persistence of the subsidiary outlet. Courtesy of V. C. Browne Ltd.

and to assess them in terms of the historical sequence of sedimentation changes reported.

Macpherson indicated that he used only soundings at Shag Rock to predict the tidal compartment, and that his data for 1874 came from a chart by Whateley Elliot. However, we have not been able to locate any 1874 chart by Whateley Elliot which shows soundings at Shag Rock; we know only of Whateley Elliot's 1874 chart giving detailed soundings at Cave Rock. As in 1854 and on several occasions between 1910 and 1938 a subsidiary channel, open at high, mid, and possibly low tide, and striking more or less along the line of the present channel, is known to have branched off the main channel just east of Shag Rock, we cannot accept with confidence Macpherson's low tidal compartment for 1874.

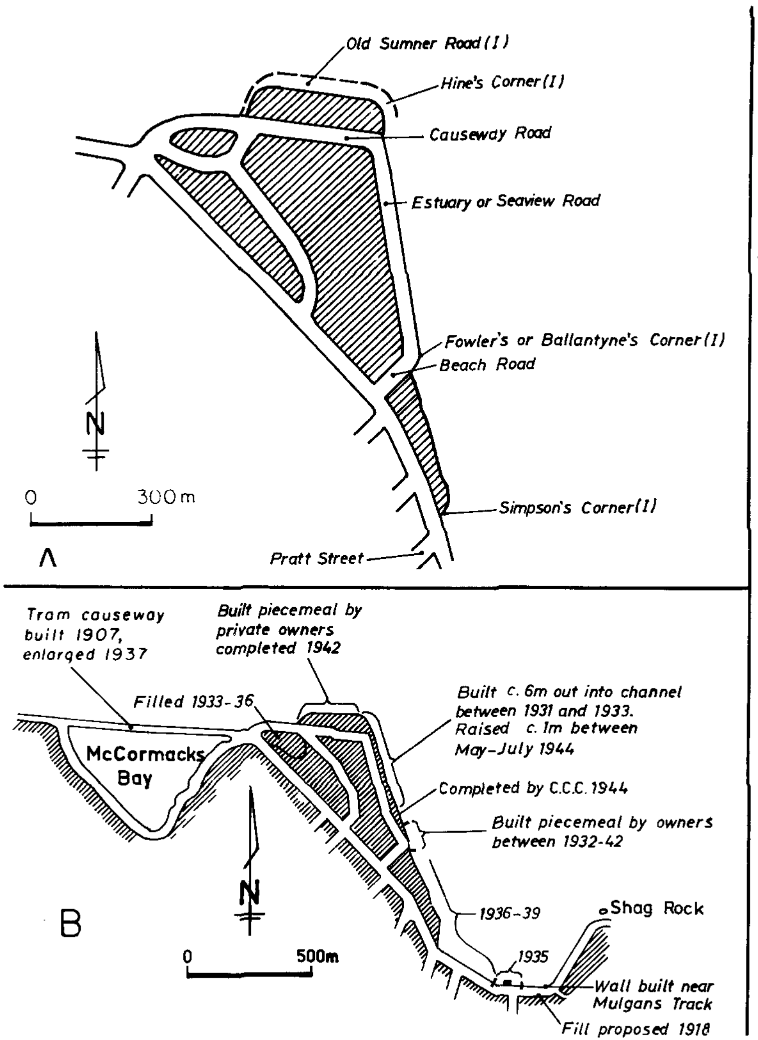
Macpherson indicated that depth soundings "on many old charts" (Macpherson 1978: caption to fig. 79) are not located accurately enough to allow the construction of detailed cross sections, and so he made his estimates of the channel's cross-sectional area by multiplying the maximum mid-tide width by the maximum depth to obtain a rectangular cross section. As the Royds & Sutherland Survey (published in 1964) had shown that in 1962 the cross-sectional area of the channel was 55% less than that of the rectangular section, Macpherson adjusted accordingly his calculated rectangular cross sections (Table 2).

We disagree with Macpherson that the depth soundings on both the 1904 and 1854 charts are not located with adequate accuracy. Both the 1904 Lyttleton Harbour Board chart and the 1854 "Pandora" survey show enough soundings to enable reasonably accurate compilation of at least two cross sections for each chart (Fig. 19 and 20). Calculations based on our sections (Fig. 19 and 20) show that Macpherson's predicted tidal compartment for 1854 is an underestimate whereas the 1904 value we have calculated from Figure 16B approximates to Macpherson's 1920 value (Fig. 18).

Macpherson used Joshua Little's 1911 measurement of the "daily outflow" to derive a tidal compartment of 4.826×10^6 m^3 in 1911. However, as Macpherson points out, Little's measurement is ambiguous as it could refer to either a 12½ or a 25-h tidal cycle. Therefore, as agreed by Macpherson, the tidal compartment in 1911 could have been as high as 9.652×10^6 m^3.

On the basis of his tidal compartment calculations, Macpherson (1978) suggests that during the early phase of settlement of Christchurch (c. 1854–1911), sediment entered the Estuary through the sewage and drainage system and reduced therefore the volume of the Estuary. As the urban area became hard-sealed and better drained, the rate of drainage would have increased, erosion in the city would have decreased, and the Estuary would have been "flushed out" by the increasing inflow of waste water, thereby increasing the tidal compartment.

Macpherson notes (see Fig. 18) a strong correlation between sewer miles laid after 1878 and his supposed rapid increase after 1911 of the tidal



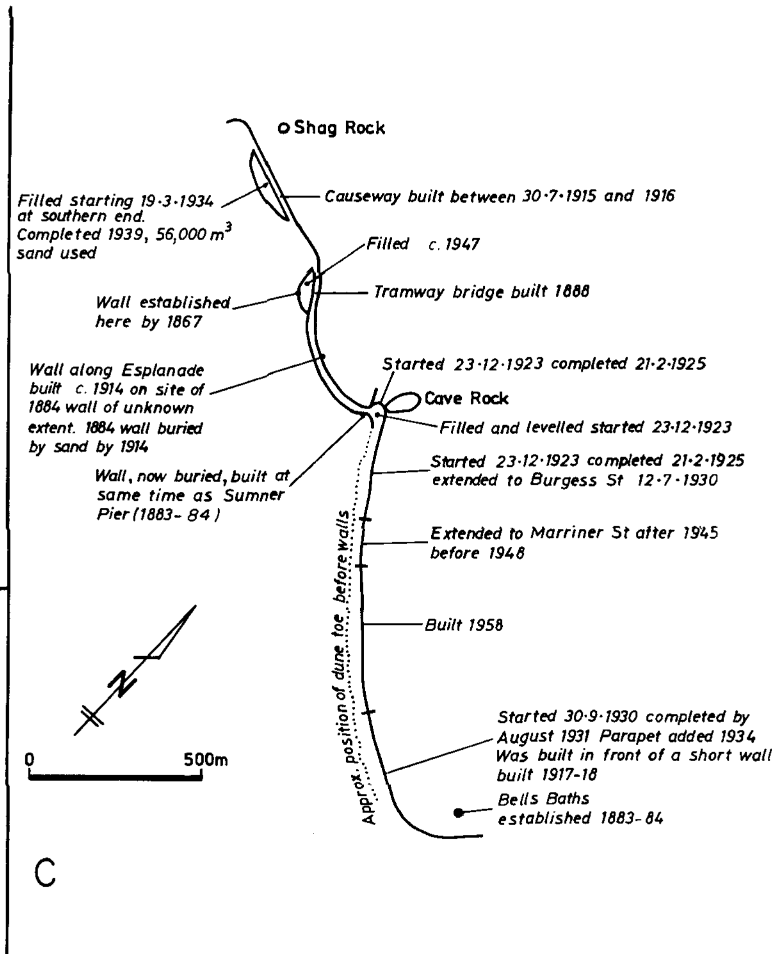


Fig. 12 **A**, Old street names in Redcliffs; informal local names indicated by (I). **B**, Construction history of sea walls built at Moncks Bay. **C**, Construction history of sea walls at Sumner.

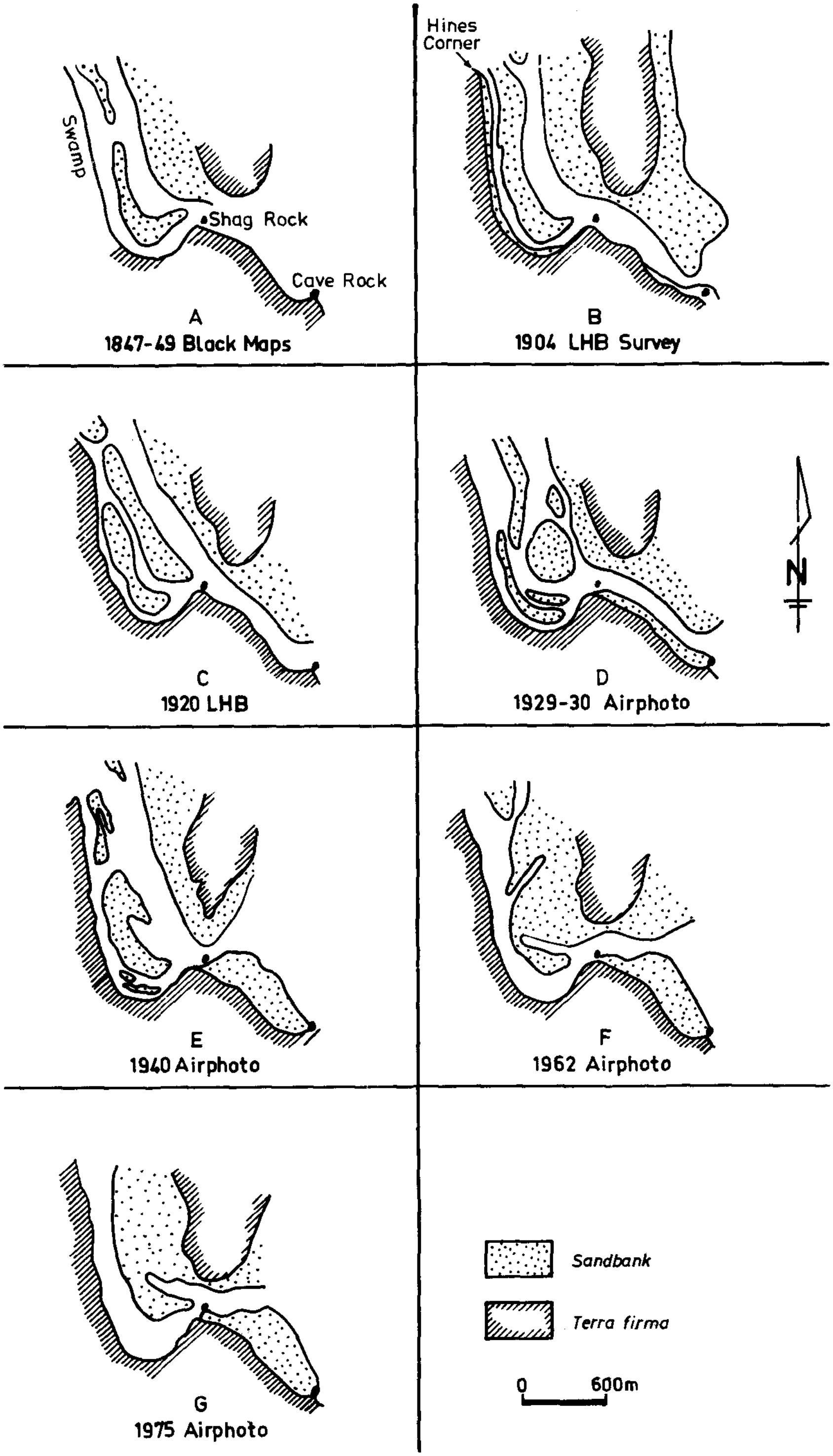


Fig. 13 Sketch maps to show channel changes in Moncks Bay 1847–1975.

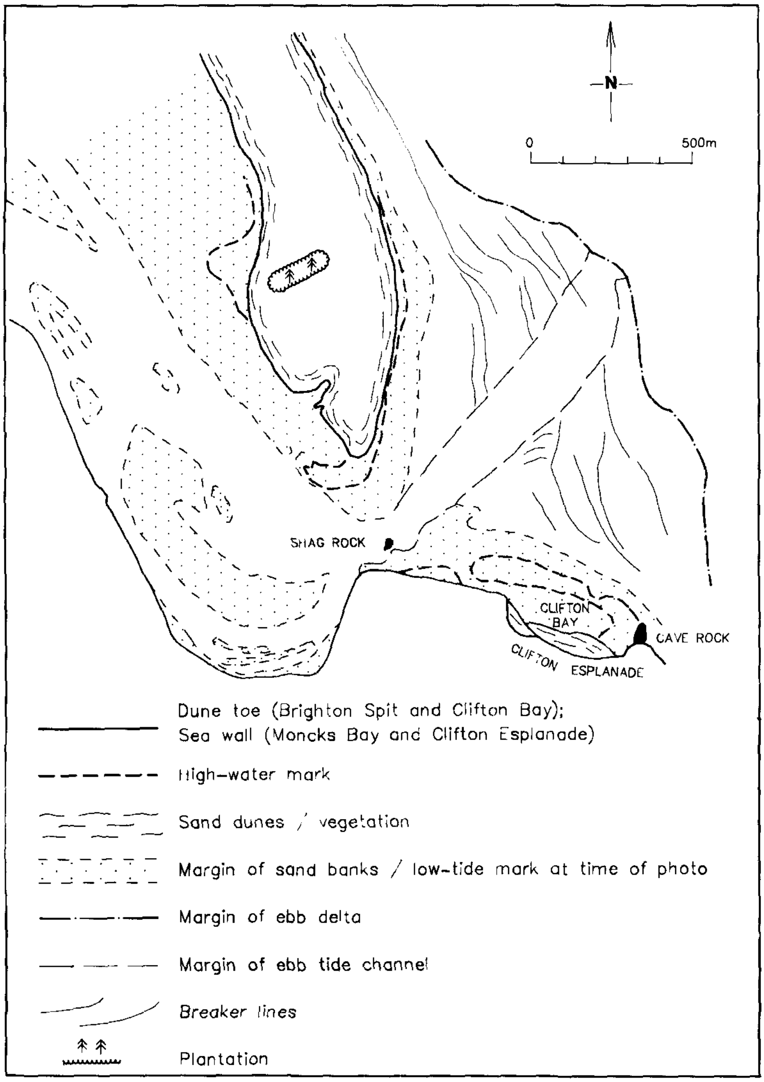


Fig. 14 Spit tip in 1940. From vertical aerial photographs.

compartment and concludes, "the subsequent rapid increase in volume of the tidal compartment was paralleled by increases in the length of the City's drainage system suggesting that there may be a fundamental link between changes in the tidal compartment and the rate of modification of the freshwater catchment of the Estuary" (Macpherson 1978: 9). That is, Macpherson suggests a simple relationship between the length of stormwater drain and sewer miles laid, changes in the tidal compartment, and presumably the rate of increase of the Christchurch urban area. However, the number of sewer miles laid does not correlate with the increase in sewage discharge, as the majority of sewer connections were not made until the mid 1950s (Fig. 18); nor need the subsurface stormwater drain mileage represent at all closely the increase in hard-sealed areas and concomitant increase in rapid stormwater run-off. A more useful comparison is to treat Christchurch as a surface at all times containing a uniform proportion of sealed area to unsealed area, view it as a growing catchment draining into the Estuary, and to plot the increase in area of Christchurch against increase in tidal compartment (Fig. 18).

Although this is a simplified approach, if there is a simple relationship between growth of Christchurch and the change in tidal compartment, the increase in tidal compartment should follow closely the increase in urban area. Fig. 18 shows that, using

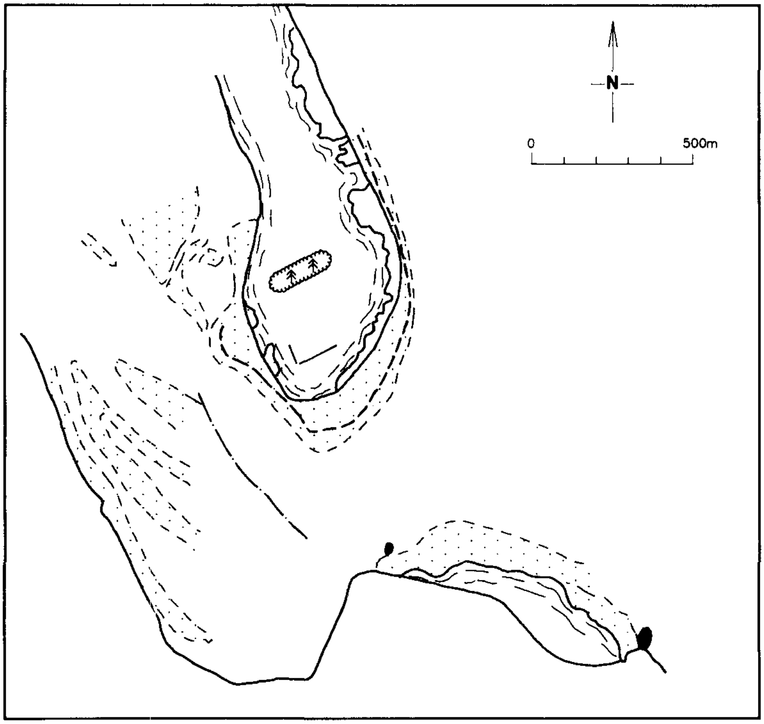


Fig. 15 Spit tip in 1946; legend as for Fig. 14. From vertical aerial photograph.

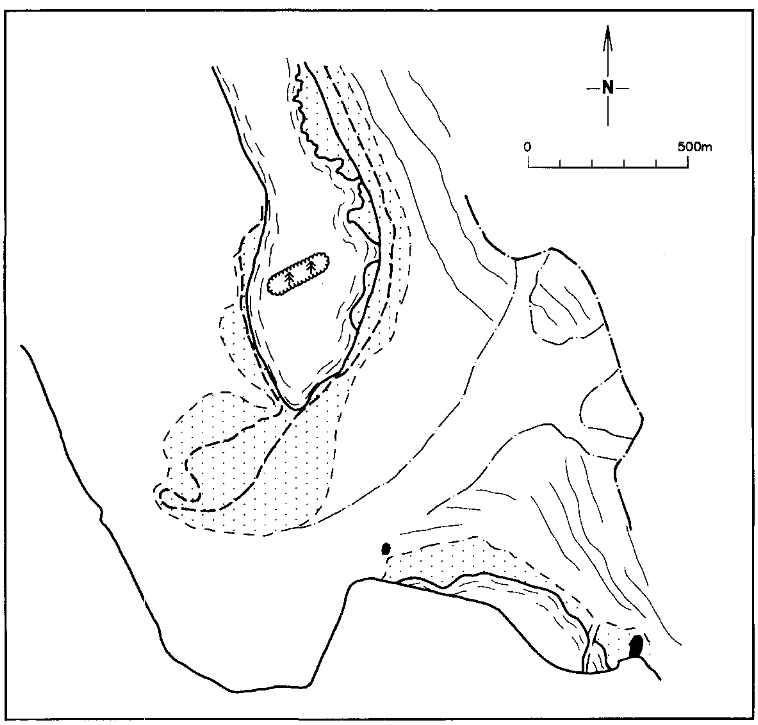


Fig. 16 Spit tip in 1951; legend as for Fig. 14. From aerial photograph. The spit recurve developed in October 1948.

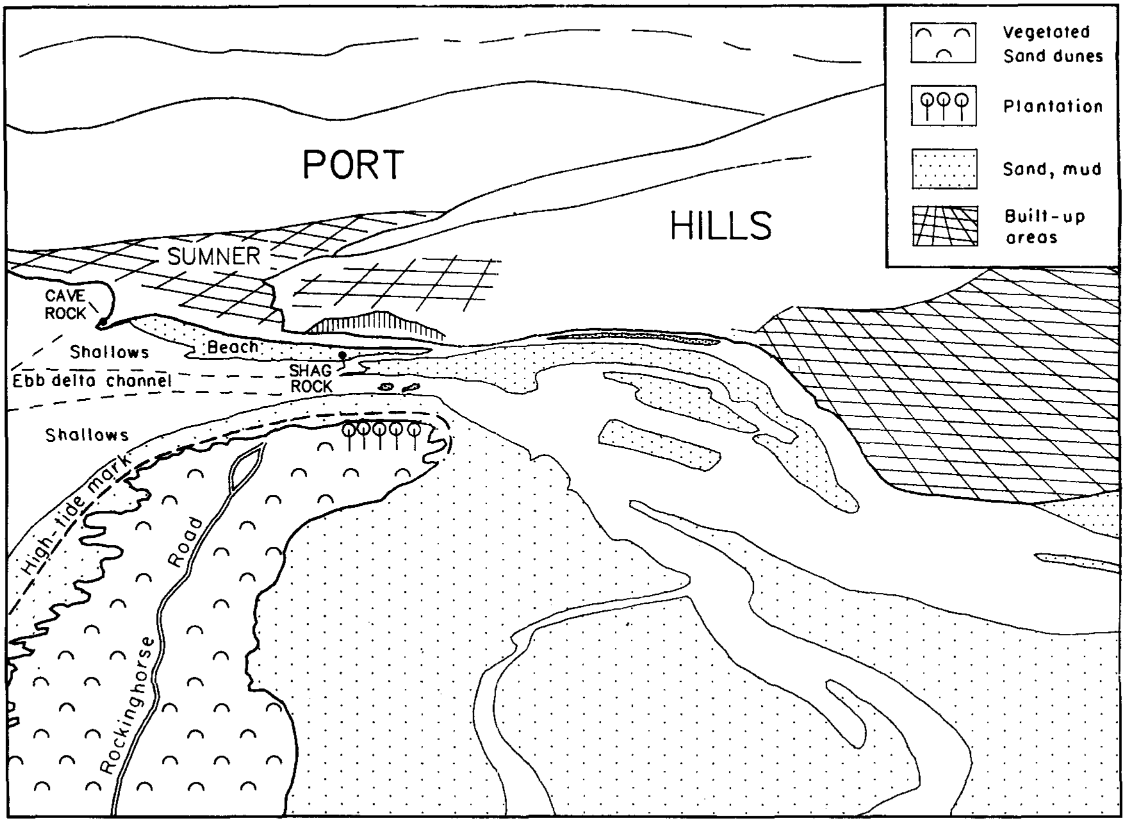


Fig. 17 Drawing of Estuary channels and Brighton Spit in July 1946. From oblique aerial photograph by V. C. Browne Ltd.

Macpherson's tidal compartment values, the rapid post-1911 increase in tidal compartment precedes by at least 15 years the acceleration in growth of Christchurch. In contrast, using our figures, the two curves (Fig. 18) are parallel until 1925–30, whereas after 1930 the urban area increased rapidly while there was a decrease in the rate of increase of tidal compartment.

This suggests that up to the 1930s there could have been a close relationship between the growing urbanisation of Christchurch and the estuary configuration. Our historical data confirm important changes to the inlet culminating in the inlet channel shift in 1938. This would imply that in the 1930s Christchurch reached a size beyond which the estuary would have had forced on it a drastic inlet change to accommodate the increasing run-off and increased waste-water discharge. This post-1930 inlet configuration is presumably relatively stable in respect of the present urban area, although we cannot predict if further increases in the Christchurch urban area will cause further changes to the estuary.

Effects of littoral drift in major changes to the estuary inlet

Littoral drift is important to the development of estuary inlets, yet is a factor difficult to evaluate for the study area from the known historical records. The problem can be discussed using the approach of Bruun & Gerritsen (1960) and Bruun (1978), who note that inlet stability is a function of the scouring power of the tidal compartment and the choking effect of the littoral drift. According to Bruun (1978: 261–262), most problems in estuarine sedimentation relate to the manner and efficiency with which sediments are moved across, or "bypass", 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 (where some may be deposited), and then jetted out on the ebb to be redistributed to the adjacent beaches. This is *tidal bypassing*, and is usually associated with large ranges in tide and with weak development of bars. In lower tidal ranges, *bar bypassing* is common: here, a prominent bar is

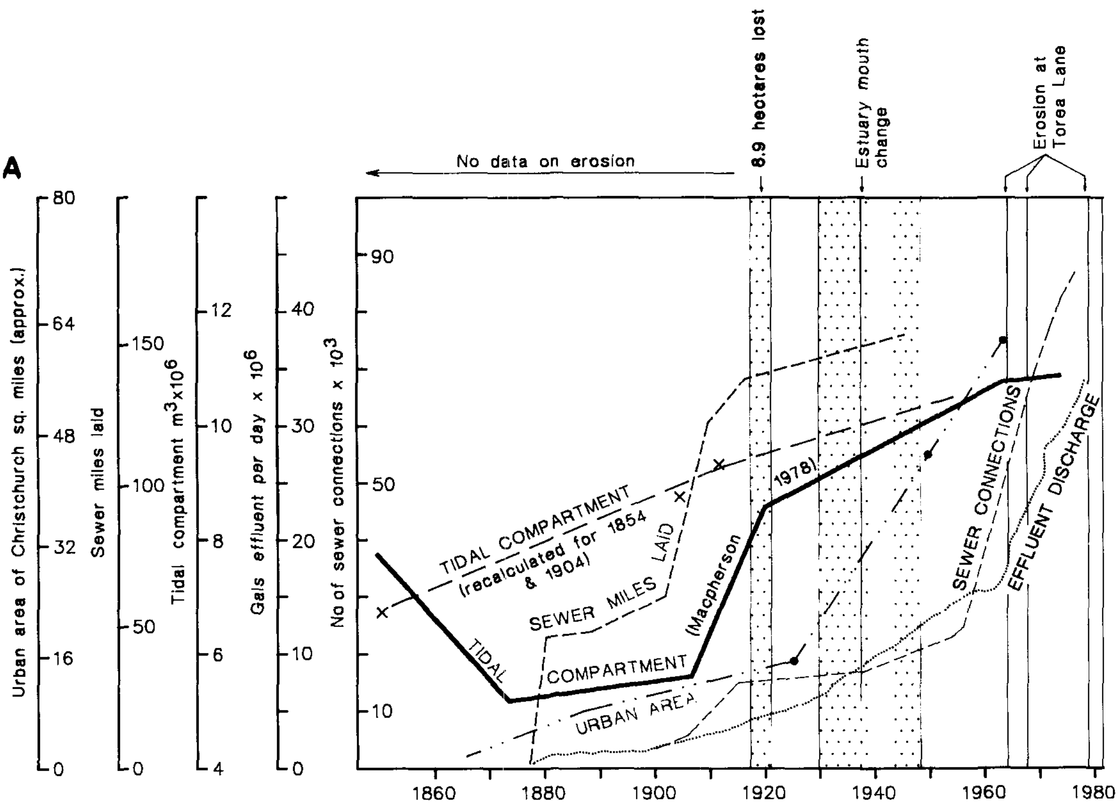
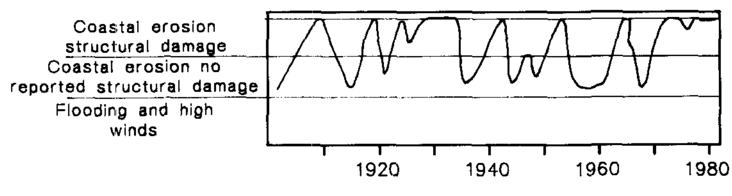
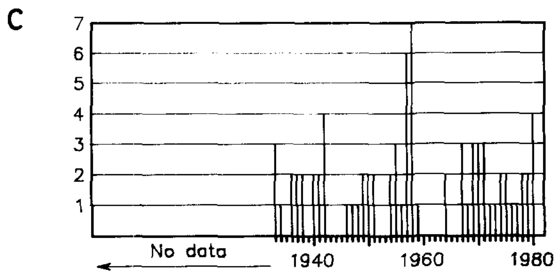


Fig. 18 A, Tidal compartment, sewer miles laid, sewer connections made, urban area from 1850 to 1981. Periods of erosion stippled; crosses show our recalculated tidal compartment. B, reported incidence of storm damage in Pegasus Bay. C, Number of floods greater than 1800 m³/s at Waimakariri Gorge.





present and sand passes to downdrift shores by transport through the bar under combined wave and current activity. In other situations, combined bar and tidal bypassing is known.

Bruun (1978) characterises the relationship of the scouring power of the tidal compartment and the choking effect of the littoral drift in part by the ratio Ω/M_{tot} where Ω is the tidal compartment in m³, and M_{tot} is the total annual littoral drift in m³. This approach differs from Macpherson (1978) and our re-evaluation of his data, in that Macpherson (1978) used inlet geometry to predict the tidal compartment, then related history of changes at the inlet to changes in tidal compartment.

Gross drift (M_{tot}) around the ebb tidal delta of the Avon-Heathcote Estuary can be approximated by the volume variations in the adjacent beaches, which are of the order of 100–200 000 m³/year, although they may be widely variable in time. Using the tidal compartments presented in Table 2,

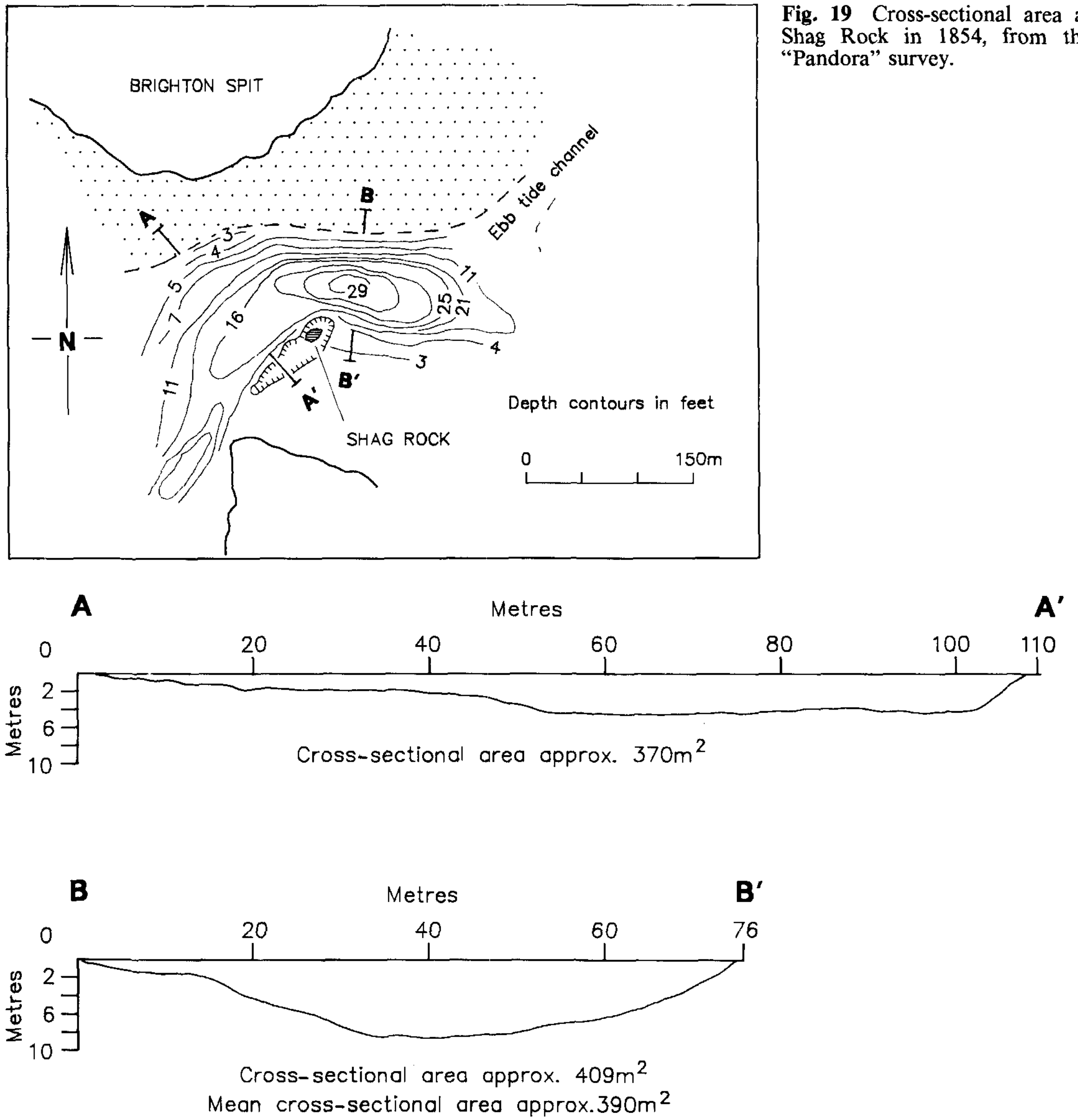
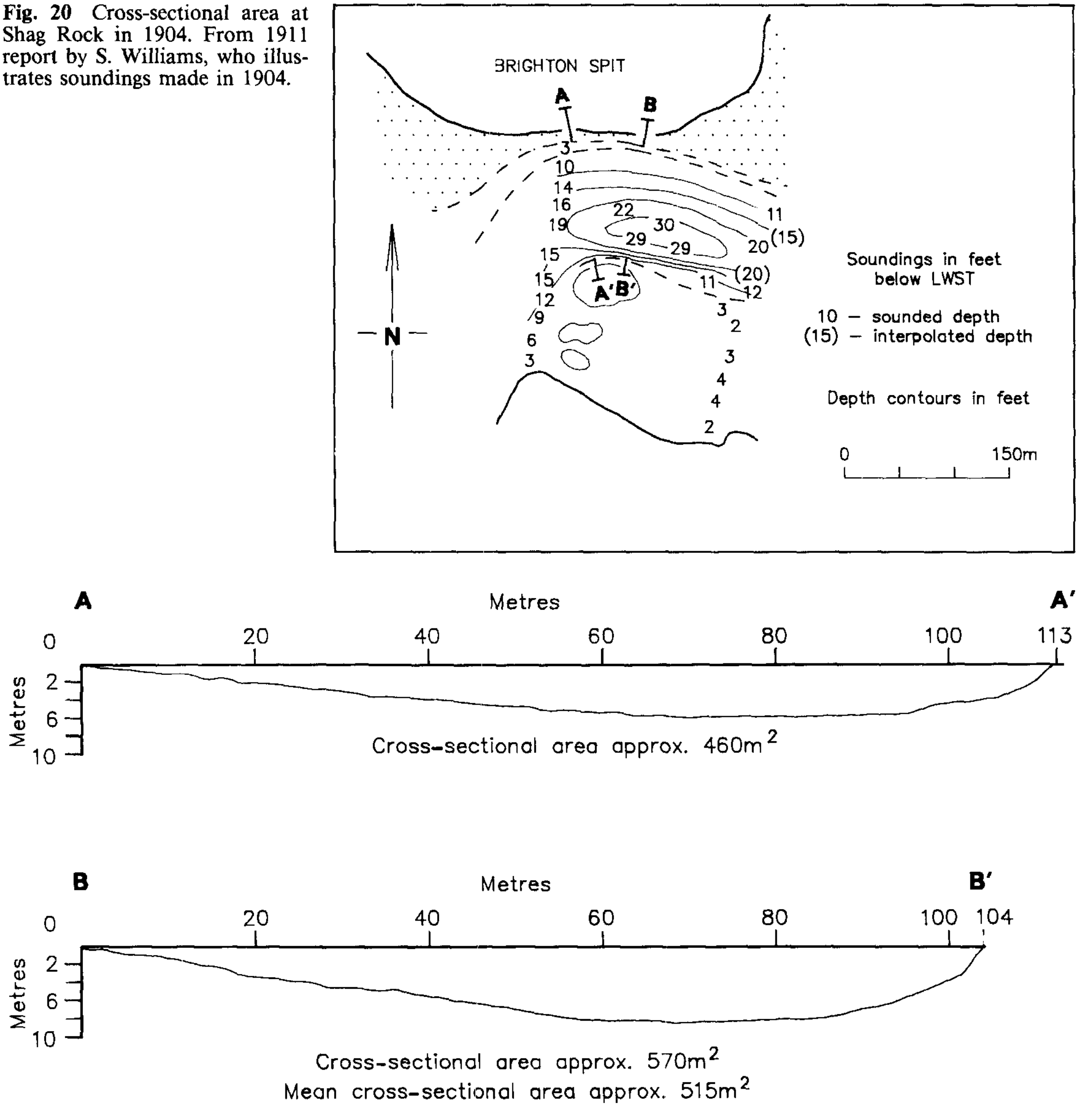


Fig. 19 Cross-sectional area at Shag Rock in 1854, from the "Pandora" survey.

200 000 m³/year for the drift, and allowing for fluvial flood discharges additional to the tidal compartment, Ω/M_{tot} ranged from 38 upwards for the early period. The inlet would therefore be of the bar bypassing type, a finding supported clearly by the existence of the large ebb tidal delta complex and the then prominent bars. For 1975–77 (Table 2), and for the same drift values, Ω/M_{tot} ranged from 55 upwards. This contrast suggests a decline in the strength of bar bypassing, and a change to a condition of mixed bar and tidal bypassing. This change can be related readily to the present configuration of the ebb tidal delta, and to the history of changes documented by us, as below.

Between c. 1850 and 1938 there existed a prominent bar extending from the Southshore spit tip to near Cave Rock. Historical records between 1851 and the late 1930s (Table 1) show that erosion at Scarborough Beach was countered regularly by slow rebuilding of the sand dunes, in spite of the increasing local urbanisation of the area. This could suggest a bar-bypassing regime was predominant, a conclusion which could well be supported by data from the period 1927–36, where massive amounts

Fig. 20 Cross-sectional area at Shag Rock in 1904. From 1911 report by S. Williams, who illustrates soundings made in 1904.



of sand built up around the Cave Rock-Clifton Pier region, and Sumner bar extended at times south of Cave Rock. After 1938 there has been minimal to no build-up of sand along Sumner Beach. This contrasts with Clifton Beach which, since the inlet redirection in 1938, can be considered as part of the ebb tidal delta complex, and where erosion and accretion appear to have alternated almost periodically. This would suggest that the 1930s to 1938 were a critical time in which the inlet regime changed from a predominantly bar bypassing one to a mixed tidal and bar bypassing one. This is also the time that we have suggested Christchurch reached a size requiring changes in the estuary outlet for dispersal of run-off.

This conclusion may be supported also by the behaviour of the spit tip. Spit recurves formed in 1934 and 1936, and were extensive enough to have interfered with the northernmost Moncks Bay channel (Rule 1980). These data, as has been documented by Kruger (1981), suggest that the ebb delta and spit tip could well have become more important than they were earlier in the century as sources for the beaches and sandbanks in Moncks Bay: that is, during the 1930s, a tidal bypassing regime was becoming dominant. It should be noted, however, that a spit recurve may have existed in the 1890s (Fig. 3), and that a small recurve formed during the erosive episode in 1918–22.

Although the most dramatic indicator of the change in inlet bypassing regime was the inlet redirection in 1938, this change may have been heralded some 27 years earlier by onset of erosion of Skylark Island. Before 1911, this island had been a feature stable enough to be used for pastoral farming, and it had been subdivided into allotments. However by 1911, the tidal compartment had increased by about one-third of its 1854 volume, circulation in Moncks Bay had been restricted by construction of the Moncks Bay causeway (1907), and erosion of Skylark Island had commenced. By 1920, Skylark Island had disappeared, and it was in 1918–22 that the first major erosion of the spit tip was recorded. That is, in the period 1911–22, there is clear evidence for unusual removal of sand from the estuary outlet. This is supported further by the good record of accretion at Cave Rock during 1910–22. These coincidences could indicate initiation of tidal bypassing as an important mechanism, and thus the years between 1911 and 1938 may represent the transition period between a dominantly bar by passing regime and the present mixed bar and tidal bypassing one.

Tidal ranges

Throughout we have assumed that tidal ranges at given points within the estuary have remained constant since 1854. This is unlikely in view of the large changes in the inlet width, particularly during the 1940s, and such changes would have had appreciable effects on the volume of the tidal compartment. Since we have no data, we are unable to do more than note this effect and to draw attention to the fact that, because of it, changes in the value for the tidal compartment cannot be simply equated to changes in the volume of intertidal sediment stored within the estuary.

Considerations for town planning purposes

The change in inlet orientation in 1938, here considered to be caused by the change in inlet regime from bar passing to mixed tidal and bar bypassing, appears to have had a profound effect on local residents and land now used for residential purposes. With the redirection of the inlet, properties at Redcliffs and in Moncks Bay became more exposed to the destructive effects of storm waves during high tides. The most dramatic effect produced was the erosion of the spit tip between 1940 and 1949, which would have been exacerbated by known military activities of uncertain extent between 1940 and 1945, a widespread scrub fire in March 1941, and unusually heavy rainfalls between 1945 and 1946 (Fig. 17). Additional problems may have been caused in 1943–45 by the lack of floods greater than 1800 m^3/s in the Waimakariri (Fig. 18). Since it has been suggested (Kirk 1979) that the Waimakariri may contribute 650 000 m^3 of sand per year to the Christchurch beaches, and most of the sediment arriving at the Waimakariri mouth is brought down by floods (Griffiths, North Canterbury Catchment Board, pers. comm. 1981), then the lack of floods in 1943, 1944, and 1945 could have starved the Christchurch beaches of sand during 1945–49, thus precluding repair of erosive damage.

It is important also to note that the orientation of the ebb tidal delta channel may have had a significant role after 1938. The end of the 1940–49 erosion of the spit tip coincided with re-orientation of the channel strongly to the north-east. That is, sand would have been discharged from the estuary to the north of the spit, and would then have been reworked south by the common strong north-westerly winds. Although our data after 1953 are too sparse to support fully this contention, the observations of a keen surfer resident in Sumner, Mr B. Wallace (pers. comm. 1981), tend to support us. He indicated that when the channel is discharging southward, the breakers form well out from the shore, whereas when the channel discharges due east or north-east, the water is deeper closer to shore at Sumner.

Since 1949, when major, sustained erosion of the spit tip ceased, the tidal compartment has almost doubled (Fig. 17) our re-calculated 1854 volume. However, since 1949 there have been no major destructive alterations to the estuary inlet, although the urban area of Christchurch has increased markedly; rather, the spit hook has consolidated, confining the outflow to what appears to be an awkward bend in Moncks Bay. This suggests firstly that the later growth of Christchurch has had a lesser effect on the tidal compartment than growth during 1860–1930 and, secondly, that the mixed tidal and bar inlet bypassing mode is at present adjusted to the drainage requirements of Christchurch.

The above conclusion notwithstanding, for town planning purposes, the inlet configuration, dependent as it is on the vagaries of a mixed bar and tidal bypassing regime, is less predictable than before 1938 when it was dominated by the bar bypassing mechanism. In the present regime, the combined effects of weather, both locally and in the headwaters of the Waimakariri River, together with the orientation of the ebb-tidal delta channel, may well act so as to destabilise the spit tip more easily than before 1938, with serious consequences for present and future housing developments in the region.

CONCLUSIONS

Our historical review has shown that the changes at the inlet of the Avon-Heathcote Estuary have been very complex. The most important change has been one from principally a bar bypassing regime to one where the present regime is a mixed bar and tidal bypassing condition. The major manifestation of this has been the change in the Sumner Bar, which before 1938 extended south to Cave Rock and provided valuable protection to land at the Southshore spit recurve and in the Redcliffs region. The diversion of the permanent inlet channel to its present position has made both the Southshore spit tip and the Redcliffs area more vulnerable to the sea, and consequently both the ebb delta geometry and climatic variations have become important factors to consider for town planning purposes.

We have also evaluated critically those changes which were thought to have indicated the influence of the growing urban area of Christchurch in the context of calculated changes in the estuarine tidal compartment, previously investigated by Macpherson (1978). In particular, his conclusion that more than 2×10^6 m^3 of sediment had been deposited in the estuary between 1854 and 1911, and that after 1916 about 6×10 m^3 was removed, giving a net change to the estuary of about 4×10^6 m^3 by 1975–77 (Fig. 18, Table 2) are disputed. Even within a predominantly intertidal estuary, the tidal compartment is not a simple function of stored sediment volume as it is sensitive to changes in tidal range which are in turn affected greatly by the inlet geometry. This may explain a problem raised earlier, in that no obvious mechanism existed by which an estuary with net sediment gain might alter to a sustained net exporter of sediment.

We have also recalculated, using the same relationship as Macpherson (1978), the values for the tidal compartment. Our results suggest a more simple pattern of increase of compartment with time. How much this increase reflects greater freshwater discharge, is not fully understood. Our principal conclusion is that the urbanisation before 1920–38 altered the inlet regime to a mixed bar and tidal bypassing one which is highly variable in effect through time, and therefore unpredictable as yet, but less stable than previously.

More generally, we conclude that it is not satisfactory to rely solely on the relationship between the tidal compartment and the inlet cross-sectional area to determine inlet stability, as this takes no account of littoral drift. In this respect, our findings support those of Bruun & Gerritsen (1960) and Bruun (1978), who argue that the ratio of the tidal compartment to the total annual littoral drift provides a better approach. We conclude that exigencies in our available data notwithstanding, our evaluation illustrates well the problems inherent in using a covariant relationship to predict values of one variable, the predicted values being then used in an interpretation of the time sequence of the original values. Neither the values for the tidal compartment, nor the inlet cross-sectional area, can be regarded properly as independent for such an analysis.

ACKNOWLEDGMENTS

The Christchurch City Council, Christchurch Drainage Board, Civil Engineering Department, University of Canterbury, and Messrs Morris and Wilson (Consulting Engineers) have all been closely involved in studies of foreshore erosion of the South Brighton Spit. This paper is based on a report (Findlay 1981, 1984) prepared for these organisations and their approval to publish the data is acknowledged gratefully.

Grateful thanks go also to Mrs S. Rule of Sumner and Redcliffs Historical Society, who provided with great enthusiasm much detailed information extracted from Mr G. F. Allen's (Sumner resident) scrapbooks, and also made available numerous maps, newspaper cuttings, and photographs. We thank Dr D. W. Lewis (University of Canterbury), and Messrs D. Jarden, M. Hullett, A. Ell, A. J. Knight, A. K. Wright and Mrs Penny (local residents), Messrs B. Penny (Lyttleton Harbour Board), G. Webley (Lands and Survey Department), and A. Greenland (Christchurch Drainage Board) for considerable help and informative discussion. Majors N. Macpherson (New Zealand Antarctic Division, Department of Scientific and Industrial Research), and E. Boyle (retired) provided useful background information about Army activities during 1939–45.

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Appendix 1 Date of establishment of landmarks, Sumner, for dating undated photographs, drawings, and paintings.

1851	Crompton's Cottage established before 1851 near Clifton Spur.
1853	Dobson lived at Dobson's House 1853–69; house built by 1853.
1883	Sumner Pier built, together with small stone walls at landward end.
1884–85	Bell's Bath established at south end of Scarborough Beach.
1864	Wreck of S. S. *Augusta* near Cave Rock.
1886	Telephone line to Sumner established along road to Sumner.
1888	Tramway bridge built across Clifton Bay (stream trams; no electric lines).
1898	Lifeboat *Rescue* in cave at Cave Rock.
1902	March 1902, Clark takes over "Clark's Hotel"; places his name on prominent sign outside hotel.
1903	September 1903, Clark leaves Clark's Hotel; sign removed.
1903	Lifeboat *Rescue* moved to Sumner Pier and shed built on pier.
1903	First "Hurst and Seagar" house built on Clifton Spur.
1906	Cafe Continental built at Cave Rock.
1907	Tramway electrified, white railings removed from Clifton Bay bridge.
1909	February 25 - lifeboat *Aid* established near Bell's Baths, Scarborough.
1909	Cafe Continental burnt down.
1915–16	Gollans Point/Shag Rock Causeway built.
1923–25	Walls built at Cave Rock.
1926	Memorial lamps placed along Esplanade at Cave Rock.
1933	Wall completed along foreshore at Scarborough.
1937	Wreck of S. S. *Muriel* on Sumner Beach.
1937	Clocktower built at Scarborough.
1935–39	Area filled between cliffs of Clifton Heights and Gollans Point/Shag Rock Causeway.

Appendix 2 Air photo and map sources used for the study.

Date	Number if known / Map title	Held by
Vertical aerial photographs		
1929		City Engineer's Department, Christchurch City Council (Note: date given incorrectly as 1926)
1940	L & S 130/50–55, 129/50–55	Department of Lands and Survey
1946		City Engineer's Department, Christchurch City Council
1951		Hydrographic Office of R. N. Z. Navy, Takapuna Xerox held by City Engineer's Department, Christchurch City Council
1953	C. D. B. 057013, 52/1	Christchurch Drainage Board
1954	C. D. B. 081003, 54/2, 081004, 54/1, 081007, 54/3, 081002, 54/4	Christchurch Drainage Board
1955		City Engineer's Department, Christchurch City Council
1960	C. D. B. 151022, 155003, 155002	Christchurch Drainage Board
1961	L & S 3149/45, 3149/46, 3150/46	Department of Lands and Survey
1965		City Engineer's Department, Christchurch City Council
1970	L & S S84/2B	Department of Lands and Survey
1972	001 V. Nats. R. N. Z. A. F. 18 May 1972, 22002	Royal New Zealand Air Force (see also Hutchinson 1972) 5 inches, 6000 feet, Christchurch Estuary R.E.
1973	L & S SN2634/0, 5-8	Department of Lands and Survey
1974	L & S SN2634	In Millward (1975). Note: this is same photograph as above
1975	L & S SN2860 I/1-2	Department of Lands and Survey
1977	L & S SN5140 I/31-33, J/30-33, K/31-34, L/33-36	Department of Lands and Survey
Maps		
1847–49	Black Maps 341, 312, 27(b)	Department of Lands and Survey
1854	H. M. S. Pandora Survey, Red Map 181	Department of Lands and Survey
1858	Chart of River Avon RM157	Department of Lands and Survey
1874	Sumner River Entrance	Lyttleton Harbour Board
1879	Survey of Brighton Spit S. O. 2573	Department of Lands and Survey
1892	Avon-Heathcote Estuary to Godley Head	Lyttleton Harbour Board, drawing 4005
1904	Sumner Entrance (soundings 1854/1904)	Lyttleton Harbour Board
1905	Plan of Cave Rock area	Lyttleton Harbour Board
1908	Lyttleton Harbour extensions, proposed wet dock at Heathcote and ship canal	Drawing 7 in Coode, Son & Mathew's report held by Lyttleton Harbour Board
1911	Boat harbour at Sumner	Lyttleton Harbour Board
1920	Plan of proposed canal in Avon-Heathcote estuary	Lyttleton Harbour Board
1921	Survey of spit tip comparing 1879 and 1921 coastline	Department of Lands and Survey file 8/15/30 - also in Pearse (1950).
1941	Plans for walls at Moncks Bay	Sumner and Redcliffs Historical Society. "Seawall file"
1942	Christchurch area S84/2	Department of Lands and Survey
1949	Sumner Entrance (soundings 1904–49)	Lyttleton Harbour Board
1951	Summary of H.M.S. *Lachlan* Survey 1951	Lyttleton Harbour Board
1954	Soundings offshore, Sumner	Lyttleton Harbour Board
1954	Sumner depth changes May 1950–54	Lyttleton Harbour Board
1856–1969	Waimakariri record 1 and 2	North Canterbury Drainage Board