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Coastal compartments: the role of sediment supply and morphodynamics in a beach management context

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Abstract
Coastal compartments provide a hierarchical framework to manage beaches and coastal ecosystems in Australia. This study examines the individual behaviour of three adjacent beaches within Shoalhaven Bight, a secondary compartment on the south coast of New South Wales (NSW). The Shoalhaven River discharges intermittently into the northernmost of the beaches, and a fluvial component is detectable within beach and foredune sands. The distribution and orientation of headlands constrains dispersal of fluvial sediments, and results in lower wave-energy conditions further south, implying limited sand transport from one beach, or tertiary compartment, to another. Two years of monthly subaerial surveys across ten different profiles and modelled storm-wave conditions during the major storms, were used to compare the response of beach volume and shoreline position. The greatest changes in volume were observed near Shoalhaven Heads and the northern ends of Culburra and Warrain-Currarong beaches. Results indicate the distinct individual response of neighbouring beaches over the two-year period, in contrast to general trends in beach behavior that might be inferred from long-term regional monitoring programs. However, they also demonstrate the limitations of short-term observations in comparison to those longer-term studies. The NSW beach systems of are some of the best understood in the world in terms of regional behaviour, as a consequence of several decades of surveys on key beaches. However, more focused local monitoring programs may be needed to establish detailed coastal sand transport, and an understanding of intermittent delivery of fluvial sand and longshore inputs and outputs, within and between different compartments.

Keywords Shoalhaven River · Sediment dynamics · Surficial sediment · Beach profiling · Embayed beaches · Storm erosion · Coastal monitoring

Introduction

A coastal sediment compartment approach provides a functional means within which to plan for the better management of coastlines. Coastal sediment compartments have been widely used in the United States (Rosati 2005), and have formed the basis of shoreline management plans in England and Wales (Cooper at al. 2002). The concept was proposed for coasts around Australia (Davies 1974), and a national hierarchical framework of coastal compartments has been developed for the entire Australian coast (Thom et al. 2018; Short 2020).

In New South Wales (NSW), the *Coastal Management Act* (2016) and the *Coastal Management Manual* (2018) stipulates that coastal management programs use the sediment compartment approach for the 46 secondary sediment compartments identified in the state, in some cases transcending local government jurisdictional boundaries. The legislation and manual emphasised the need to understand sediment transfers within secondary compartments, and indicated that sediment sources, sinks and pathways were likely to differ both between compartments, and within smaller embayments, called tertiary compartments, often corresponding to individual beaches.

Beaches represent some of the most dynamic environments on Earth. On the microtidal wave-dominated southeastern coast of Australia, the morphodynamic behaviour of

Sustaining coastal and marine environments in the Anthropocene.

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sandy beaches has been studied in detail (Wright and Short 1984). Beaches normally erode rapidly during storms, and recover slowly during calmer conditions (Thom and Hall 1991), with recovery following particularly severe storms such as those in 1974 and 1978 taking decades (McLean and Shen 2006). Exposure to coastal erosion on open-coast NSW beaches is expected to increase into the future due to the influence of sea-level rise on shoreline recession (Kinsela et al. 2017).

Beach and dune systems in NSW occur on several sand-barrier types formed in the Late Quaternary, ranging from prograded to receded barriers (Chapman et al. 1982). The barriers have been described, together with depositional models of the estuaries that are associated with them (Roy 1984; see also Woodroffe et al. 2022, and references therein). Southern NSW comprises sequences of embayed beaches separated by rocky headlands, whereas northern NSW consists of fewer headlands and longer beaches (Carvalho and Woodroffe, 2015) where the southeasterly waves result in longshore drift and net accretion at the downdrift northern end of embayments (Short and Masselink 1999; Thom et al. 2018). The embayed beaches of southern NSW tend to be more 'swash'-aligned'. However, variations in wave climate associated with phase shifts in the El Nino-Southern Oscillation Index (ENSO) lead to cross-shore sediment movements and beach re-orientation, referred to as "beach rotation" (Ranasinghe et al. 2004; Harley et al. 2011, 2015a).

The interrelationships between beach-profile morphology, wave energy and alongshore sediment grain-size distribution have been known for a long time (Bascom 1951). Beach slope is generally related to sediment grain size and ambient wave energy; these relationships were clarified for beaches in NSW by the studies of Wright and Short (1984), and subsequent researchers (see Short 2007). Foundational studies in the 1970s commenced data collection over 4–5 decades. Repetitive surveys of beach and foredune profiles on Bengello Beach near Moruya (35.8ºS) provide a record of beach volume response to major erosional events and the subsequent slower recovery (Thom and Hall 1991; McLean and Shen 2006; see also Woodroffe et al. 2022). Similar repeat surveying of Narrabeen-Collaroy Beach in Sydney (33.7ºS) enabled the detection of adjustments to wave conditions and subtle response in orientation to ENSO (Short et al. 1995; Short and Trembanis 2004). Ongoing monitoring with state-of-the-art technologies at that beach continues to provide insights into the morphodynamics of a typical embayed beach in the Sydney metropolitan area, including the potential input of sediment from the shoreface during large storm events (Harley et al. 2015b, 2022).

Despite these long-term studies, there is not a simple approach that coastal managers could adopt to apply results from these well-studied systems to management issues on other intervening beaches. Future shoreline change response remains challenging given the complex local-scale variability in seabed geomorphology and sediment distribution, which influences whether the shoreface is a source or sink for coastal sediment during rising sea level (Kinsela et al. 2020). Comparison of behaviour on several embayed beaches shows some tendencies for similar behaviour, for example in terms of rotation (Short et al. 2014), but the extent to which individual beaches do, or do not, adjust is not fully understood. Local councils need to design their own program of monitoring where they require insight into the behaviour of beaches under their management (see for example, Gangaiya et al. 2017). Recording changes in morphological characteristics requires frequent observations of the whole beach over considerable periods. A key consideration for the design of monitoring efforts is whether adjacent beaches (tertiary compartments) within a geographical region, such as a secondary compartment, react similarly to local forcing (Ruggiero et al. 2005; Bracs et al. 2016).

This study investigates short-term adjustments on three embayed beaches (tertiary compartments) within Shoalhaven Bight (a prominent secondary coastal compartment) on the south coast of NSW. It examines the effects of intermittent delivery of fluvial sediments from the Shoalhaven River to the northernmost of the three beaches, based on textural and sedimentological analyses. The three adjacent embayed beaches represent the seaward expression of different sand barrier types, and experience markedly different levels of wave energy and beach state. Monthly beach-profile surveys, conducted over two years, were used to compare the response of the individual beaches to regional wave-forcing events. The study provides an example of how the sediment budget can differ between, and in some cases along, specific beach compartments.

Study area

The Shoalhaven coastal compartment is located on the south coast of NSW (NSW02.04.05 in the national hierarchy, Short 2020); the compartment extends for 32 km from the sandstone headland of Black Head at Gerroa (north) to the sandstone cliffs of Beecroft Peninsula near Currarong (south). This coastal sector is composed of three adjacent beach-barrier systems separated by the less prominent siltstone headlands of Crookhaven Heads and Penguin Head (Fig. 1).

Sea level rose to its present level by ~7,500 years BP at the culmination of the Holocene marine transgression, and may have reached a maximum of +1.5 m during a sea-level highstand that lasted until approximately 2,000 years BP, before gradually falling to present level (Sloss et al. 2007). The northernmost beach, Seven Mile Beach-Comerong Island, fronts a prograded barrier (Fig. 1) that has formed a series of foredune ridges (or strandplain). The

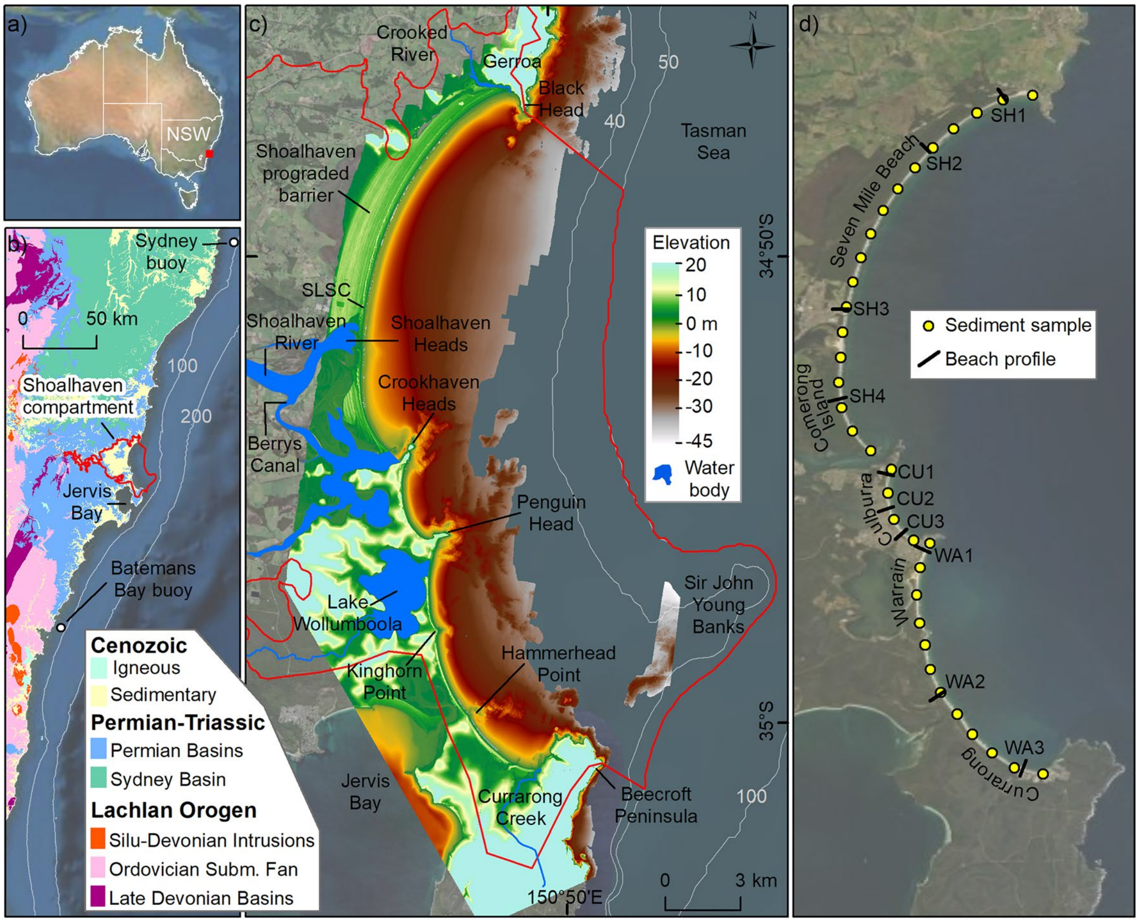

Fig. 1 **A** Study site location on the NSW coast. **B** Simplified geology showing location of the secondary level Shoalhaven Coastal Compartment (red outline) and Sydney and Batemans Bay waverider buoy. Isobaths in metres. **C** Combined topographic and marine LiDAR showing coastal landforms and general bathymetry of the shoreface. **D** Sediment samples and beach profile locations (SH1-SH4; CU1-CU3; WA1-WA3) at each individual beach

landwardmost ridge formed around the time that sea-level stabilised (McBride et al. 2021). Successive ridges have formed as sand was worked onshore during the mid Holocene, with the rate of progradation increasing as a result of the Shoalhaven River contributing additional sand to the coast over the past couple of millennia, since the estuarine plains has been largely infilled (Wright 1970; Thom et al. 1981; Carvalho et al. 2019; Carvalho and Woodroffe 2020a).

Airborne LiDAR reveals subtle topography which indicates that the Shoalhaven River initially discharged to the sea at Crookhaven Heads, until construction of Berrys Canal in 1822 (forming Comerong Island), after which it adopted a more direct route through an intermittently-open mouth at Shoalhaven Heads (Carvalho and Woodroffe 2020a). The former mouth of the river at Shoalhaven Heads is frequently blocked by deposition of a sandy berm and overwash flats; the outlet is breached temporarily only following major floods, with the beach berm subsequently re-establishing (Carvalho and Woodroffe 2013).

The topographic and sedimentological character of the sand deposits flanking the mouth of the Shoalhaven River were first described by Wright (1970), who perceived that after a breaching event, sediments accumulate in the form of a crescentic river-mouth bar and post-depositional shoreward return of sands by shoaling waves produces a constricted outlet (Wright 1977). The river is capable of delivering large amounts of fluvial sediment to the coast during major floods, changing nearshore depths (breaching events in 2013 and 2015 resulted in a loss of approximately 165,000-200,000 m^3 of beach sand to the nearshore, Carvalho and Woodroffe 2017). Rebuilding of the beach-berm leaves a pronounced dune scarp on the adjacent beach, as sand is eroded off the beach to fill the river-mouth opening. This erosion poses a severe hazard to the local life-saving clubhouse.

At Shoalhaven Heads, the east-facing beach has a transverse bar and rip (TBR) or longshore bar and trough (LBT) modal state, while at the south of Comerong Island, the northeast-facing beach has a transverse bar and rip (TBR) or rhythmic bar and beach (RBB) morphology cut by periodic rip currents (Short 2007). Northern Seven Mile Beach is a wide dissipative beach (Short 2020). A small creek, Crooked River, discharges to the north of Seven Mile Beach, near Gerroa, but delivers negligible sand.

The beach-barrier system at Culburra, south of the Shoalhaven River, is considered to be a receded barrier due to the narrowness of the barrier with a single foredune ridge, and reports that it has over-ridden a back-barrier estuarine mud unit (PWD 1980). Culburra is an east-facing beach that is usually transverse bar and rip (TBR) in the north and middle, frequently with rip currents every 200–300 m. The north-facing section of the southern end of Culburra Beach is usually low-tide terrace (LTT) and has lower waves and fewer rip currents (Short 2007).

The Warrain-Currarong Beach is east-facing in the north (Warrain), but with less wave energy at the southern end (Currarong) which faces northeast. Warrain is usually in a low-tide terrace (LTT) or transverse bar and rip (TBR) state with rip-current spacing of 200–300 m; Currarong Beach is generally low-tide terrace (LTT) with rip currents decreasing in occurrence and strength to the south (Short 2007). Lake Wollumboola, a saline coastal lagoon of approximately 6 km^2, does not deliver sand to the coast; a minor delivery may occur from the much smaller Currarong Creek estuary (0.03 km^2), near Currarong (Roper et al. 2011).

Morphological changes of beach state were briefly described by Wright (1967). Beach profiles and sediment investigations at the three beaches were undertaken twice over the course of a year as part of a thesis by Johnson (1974). An assessment of Culburra Beach was undertaken by the Public Works Department (PWD 1980). Wright and Short (1983) and Carvalho et al. (2015) provide some further description of Seven Mile Beach-Comerong Island. Apart from these sporadic observations, there has not been sufficient previous monitoring of the northern, middle and southern parts of the three beaches continuously during a sufficient period to record dynamic seasonal or longer-term changes.

The south coast of NSW is exposed to relatively large south/southeasterly swells. The relatively narrow continental shelf adjacent to Seven Mile Beach is approximately 32 km wide, with a break of slope around 130 m depth (Davies 1979). Submerged rock reefs cover approximately 18% (46 km^2) of the marine substrate (Carvalho 2018). A topographic high known as Sir John Young Banks, composed of submarine rocks, extends for 12 km to the northeast of Beecroft Peninsula. Vast quantities of quartzose sand occur on the inner continental shelf of NSW down to depths of 70 m. There are three types of deposits: (i) moderately to well sorted iron-stained sands occupy a concave-up nearshore zone down to 15–30 m depths; (ii) poorly sorted iron-stained coarser sand grain occurs in the gently sloping inner shelf surface down to 70 m; and (iii) fine to medium grained linear shore-parallel 20–30 m thick shelf sand bodies, which are typically associated with headlands (Roy and Stephens 1980; Roy 2001; Whitehouse 2007).

Methods

Sediment sampling and laboratory procedure

Approximately 150 g of surficial sand was collected at 34 locations (at ~ 1-km spacing) in the swash zone of the three beaches in July 2014 (Fig. 1). Sampling involved using a hand scoop and recording the position with GPS. In the laboratory, samples were washed to remove salt, subsampled, dried and photographed under an optical microscope. The coarse fraction of each sample was dry-sieved at 0.5 phi intervals, and the size fractions finer than 0 phi (2 mm) were determined by laser scanning using a Malvern Mastersizer 2000. Grain-size statistics were calculated using the Folk and Ward (1957) formulae in the Gradistat grain-size distribution and statistical software (Blott and Pye 2001).

The sedimentology of these sand samples has been described in detail by Carvalho and Woodroffe (2020b), 2021), and the beach samples have been compared with sand sampled from locations within the estuarine stretch of the Shoalhaven River (Carvalho and Woodroffe 2020a). Whereas well-rounded quartz dominates most of the beaches of NSW, and can be considered marine in that it has been reworked in the nearshore and on the shoreface, rivers deliver a more 'lithic' sand that can be distinguished in terms of its mineralogy and the angularity of grains (Roy 1994). Accordingly, selected samples were ground using a Tema mill and examined for mineralogical composition by X-ray diffraction (XRD), using a Phillips 1150 PW Braggs-Brentano diffractometer with CuKα radiation. Results were corrected to the appropriate 2 theta spacing using Traces software. The weathering and angularity of quartz grains from the selected samples were analysed using a JEOL scanning electron microscope (SEM) JCM6000. Grains were placed in rows upon a metal specimen plug, coated with gold, and analysed using a high vacuum mode to generate Secondary Electron Images (SEI).

Beach monitoring

Monthly beach-profile surveys were undertaken between December 2013 and November 2015 (Carvalho 2018, 2021) using GPS at all three beaches (Fig. 1). The four profiles at Seven Mile Beach-Comerong Island (SH1-SH4) were at the same locations as those undertaken by the Water Research Laboratory of University of New South Wales in 2011–2012, when they undertook a study to compare other NSW beaches with beach behaviour at Narrabeen-Collaroy Beach (Carvalho et al. 2015). Three new profile locations (north, middle and south) were monitored at Culburra and Warrain-Currarong beaches. A total of 20 surveys was undertaken at an average interval of 36 days (Table 1), augmented by photographs of the beach on each survey (see Supplementary material).

Beach elevation along profiles was surveyed at low tide; measurements were taken at 1-m intervals across the beachface and the toe of the foredune, using a Trimble Real-Time Kinematic (RTK) GPS. Elevations were reduced to Australian Height Datum (AHD), a datum that corresponds to mean sea level as determined by a nation-wide levelling survey between 30 tide gauges in the late 1960s. Beach volume estimates were calculated as the cross-sectional area above AHD, converted to volume for a metre-wide swath; and shoreline displacement measurements used the linear distance at which the beach profile intersected AHD. Technical problems prevented the collection of data during specific months at some locations, as a result no surveys were conducted during June 2014, January 2015, April 2015 and May 2015.

Wave data and modelling

Wave data from the wave buoy located offshore of Batemans Bay, 100 km south of Shoalhaven Heads (Fig. 1) were provided by Manly Hydraulics Laboratory. Data covering the period between 2013 and 2015 were used to characterise storms (Fig. 2; Table 2) and as input to generate wave-refraction diagrams. Between December/2013 and December/2015, nine major storms (wave power > 10×10^4 kW/m) impacted the coastline. Owing to technical malfunction between July and October/2015, the last two major storms were not recorded by the Batemans Bay buoy. Data were extracted, instead, from the Sydney offshore wave buoy (130 km to the north of the study site) to complete the series of major storms presented in Table 2.

A finite-difference Steady-State Spectral Model (STWAVE), formulated on a Cartesian grid (0.5 km) and based on the wave action balance equation that simulates depth-induced wave refraction and shoaling (Smith et al. 2001) was used to estimate nearshore wave propagation. The model describes quantitatively the change in wave parameters between the offshore and nearshore, producing wave-refraction diagrams for different wave conditions. Geoscience Australia's 250 × 250 m bathymetric grid (Whiteway 2009), wave data from Manly Hydraulics Laboratory, wind data and tidal amplitude were used as input for the model.

Table 1 Beach-profile surveys undertaken at Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong beaches between 2013 and 2015

Survey dates	Profiles Seven Mile Beach- Comerong Island				Profiles Culburra			Profiles Warrain-Currarong		
	SH1	SH2	SH3	SH4	CU1	CU2	CU3	WA1	WA2	WA3
7–8/12/2013			x		x	x	x	x	x	x
3–4/01/2014	x	x	x	x	x	x	x	x	x	x
1–2/02/2014	x	x	x	x	x	x	x	x	x	x
1–2/03/2014	x	x	x	x	x	x	x	x	x	x
29–31/03/2014	x	x	x		x	x	x	x	x	x
25–26/05/2014	x	x	x	x	x	x	x	x	x	x
12–14/07/2014	x	x	x	x	x	x	x	x	x	x
13–14/08/2014	x	x	x	x	x	x	x	x	x	x
9–10/09/2014	x	x	x	x	x	x	x	x	x	x
8–9/10/2014	x	x	x	x	x	x	x	x	x	x
7,19/11/2014	x	x	x	x	x	x	x	x	x	x
6–7/12/2014	x	x	x	x	x	x				
4–5/02/2015	x	x	x	x	x	x	x	x	x	x
20–21/03/2015	x	x	x	x	x	x	x	x	x	x
11–12/06/2015	x	x	x	x	x	x	x	x	x	x
9–10/07/2015	x	x	x	x	x	x	x	x	x	x
2–3/08/2015	x	x	x	x	x	x	x	x	x	x
25/09/2015	x	x	x							
29–30/10/2015	x	x	x		x	x	x	x	x	x
26–29/11/2015	x	x	x	x	x	x	x	x	x	x

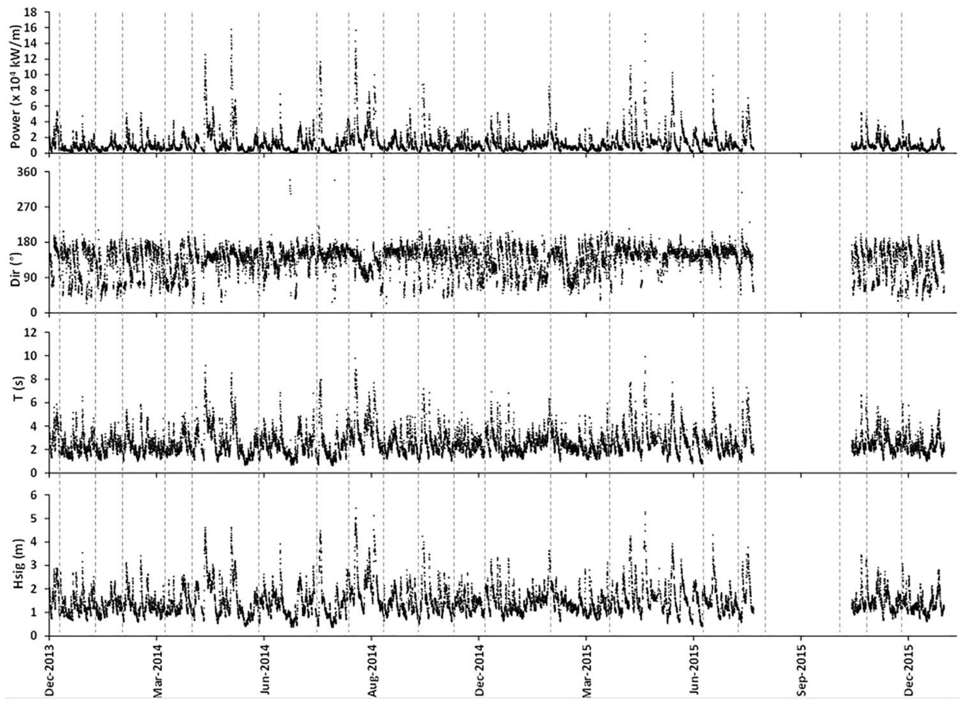

Fig. 2 Offshore wave data recorded at Batemans Bay between 2013 and 2015. Vertical dashed lines represent beach surveys taken at Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong beaches

Table 2 Characteristics of storms whose wave power was higher than 10×10^4 kW/m. Significant wave height (Hsig), Period (T) and Direction (Dir) values from specific storms were extracted from the moment wave power peaked. Storm duration was calculated as the number of hours Hsig exceeded 3 m

Date	Hsig (m)	T (s)	Dir (°)	Peak power ($x10^4$ kW/m)	Storm (Hsig > 3 m) duration (hours)
12/04/2014	4.6	11.4	131	12.5	49
04/05/2014	4.6	14.8	152	15.8	30
19/07/2014	4.5	12.9	161	11.6	35
18/08/2014	5.4	10.8	144	15.6	49
09/04/2015	4.2	12.1	152	11.1	33
21/04/2015	5.3	11.4	149	15.1	20
14/05/2015	3.9	13.8	151	10.3	33
17/07/2015	4.6	10.3	189	10.5	43
30/08/2015	4	13.8	185	10.1	49

Results

Sediment characteristics

Figure 3 summarises the subtle longshore variations in surficial sediment characteristics of the three beaches. In terms of grain size, the coarsest sample (1 phi/2 mm) occurred on Warrain (B11) near Lake Wollumboola, with the finest (2.4 phi/0.19 mm) near Currarong (B2). Grain size increases towards the northern ends of Culburra and Warrain-Currarong, and fines towards the north and south of the former river mouth at Shoalhaven Heads. At Seven Mile Beach-Comerong Island, the coarsest sample was located 1.5 km north of Shoalhaven Heads (B23) entrance (1.21 phi), whereas medium sands (> 1.5 phi) are found up to 5 km northwards of that (Fig. 3a).

Sand was mostly moderately well sorted (0.46 phi to 0.83 phi, Fig. 3b), with well-sorted samples towards the northern ends of the beaches. All beach samples but one were symmetrical (symmetrical values varied from − 0.05 to 0.03, Fig. 3c), and all had a normal distribution (mesokurtic), without coarse (gravel) or fine (mud) tails to the grain-size distribution (Fig. 3d-f).

Substantial contrasts in colour were apparent when beach samples were laid out side by side, tending brown in colour at Seven Mile Beach-Comerong Island, and orange in colour at Culburra and most of the Warrain-Currarong Beach (with a brown colour again in the samples near Currarong, Fig. 3g-h).

A majority of quartz grains on the beach observed by SEM were well rounded, as also observed for grains from the shoreface (Carvalho and Woodroffe 2021). For example, grains present in the sample at Culburra (B14) had low to medium sphericity. Roundness varied from rounded to sub-angular, however most grains were sub-rounded. Chemical weathering was absent or very light. Polished surfaces were present in most of the grains. At Warrain (e.g. B11), grains were similarly well-rounded to sub-rounded and had mostly low to medium sphericity, but grains at Currarong (B2) were very different in that sphericity varied from low to high and roundness was angular to rounded.

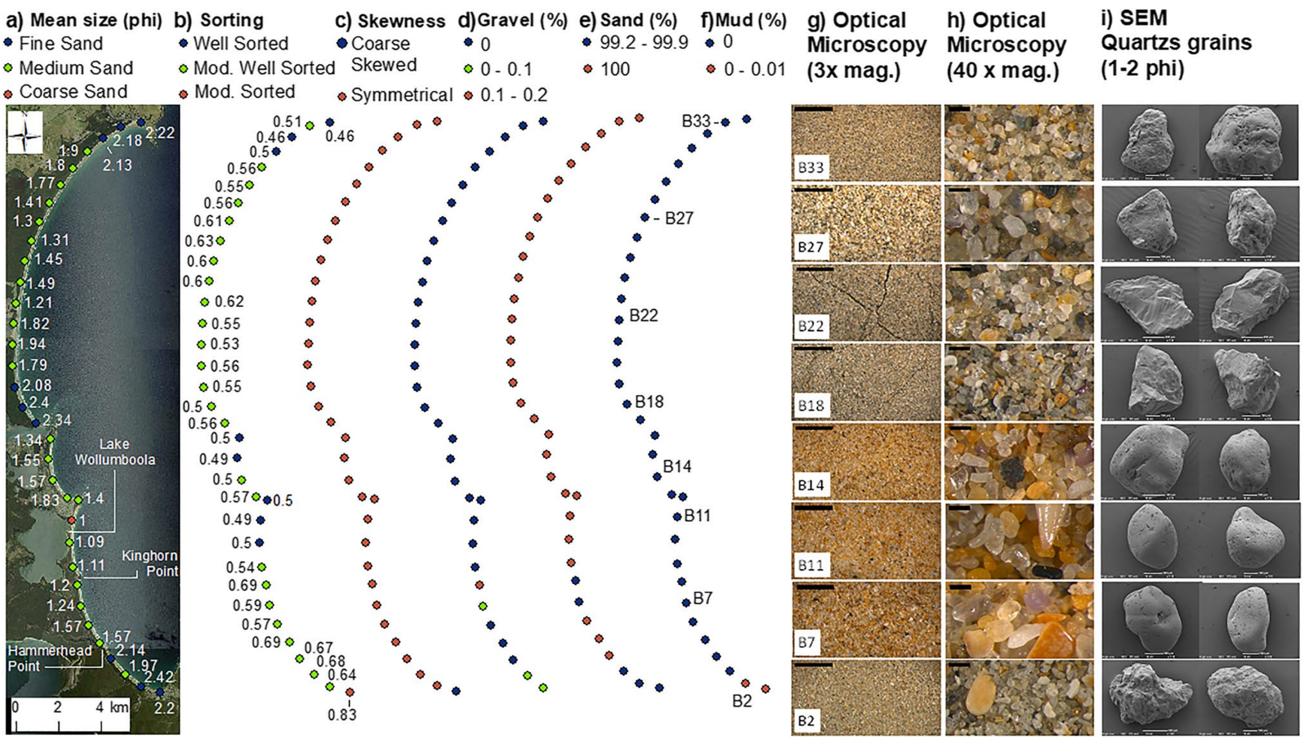

Fig. 3 Surficial beach sediment texture, colour and shape. Mean grain size (**a**), sorting (**b**) and skewness (**c**). Percentage of gravel (**d**), sand (**e**) and mud (**f**) content in each sample. Optical microscopic photographs of selected samples at 3x (**g**) and 40x (**h**) magnification. Scale bars in upper left corresponds to 10 mm (**g**) and 500 µm (**h**). SEM images of quartz grains in the 1–2 phi fraction within the selected samples (**i**)

By contrast, grains at Shoalhaven Heads (B22) had low sphericity and were very angular to sub-angular. Some of the grains showed signs of strong chemical weathering, whereas others had fresh surfaces. The grains present on the beach at Comerong Island (B18) were slightly more spherical than the ones adjacent to Shoalhaven Heads (B22), but roundness and chemical weathering were similar. A fuller range of SEM images can be viewed in Carvalho and Woodroffe (2020b).

Sediment provenance

The Shoalhaven River was considered to be the source of most of the sand composing Seven Mile Beach-Comerong Island by researchers in the 1970s (Wright 1970; Johnson 1974). A sediment budget calculated for the Shoalhaven River catchment using geospatial techniques by Carvalho and Woodroffe (2021) estimates that between 1981 and 2006, at least 1,000,000 m^3 was discharged from the intermittently-open river mouth onto the shoreface. Our results show that angular sands delivered from the river are reworked towards the north and also onto Comerong Island. Sand grains decrease in size and increase in sorting with increasing distance from Shoalhaven Heads (Fig. 3). No pattern of chemical weathering alongshore could be discerned for Seven Mile Beach-Comerong Island but some of the quartz grains had chemically weathered surfaces very similar to those observed on the grains in the lower Shoalhaven River estuarine channel (Carvalho and Woodroffe 2020a, b).

Sand sourced from the Shoalhaven River is retained primarily within the northernmost of the three tertiary compartments. Sand on Culburra and Warrain-Currarong Beaches appears different from that on Seven Mile Beach-Comerong Island (Fig. 3i), grains being much more rounded and spherical (e.g. samples B14, B11 and B7), suggesting very mature sediments that have been considerably reworked. We interpret the orange colour of the quartz sands (e.g. samples B14, B11 and B7, Fig. 3g-h) to be iron-staining, indicating its relict origin (chemical weathering and the browner colour observed in some grains from sample B2 (Fig. 3i) located at Currarong may indicate some sediment contribution from the nearby creek).

Quartz is the most abundant mineral found in the analysed beach samples with concentrations of 58.6–88.1% (Table 3). Mineral composition of selected samples indicates further support for the delivery of lithic sands by the river. Feldspars, of which orthoclase was the most abundant (1.6–4.2%), were present in all samples, but were more abundant in Seven Mile Beach-Comerong Island (8.7–9.7%) than in the other two beaches (4.1–6.5%). The high feldspar

Table 3 Mineralogy of beach surficial sediments (wt%) of size fraction finer than 0 phi. Feldspars include orthoclase, albite, labradorite and microcline

Sample	Chi square	Quartz	Felds pars	Calcite	Mg Calcite	Arago nite	Musco vite	Illite	Kaoli nite
B33	2.8	84.4	9	0.4	0.6	0.6	1.9	1.8	1.2
B27	2.74	88.1	8.8	0	0.1	0	0	2.4	0.5
B22	2.71	87.9	8.7	0	0.4	0	0	2.3	0.7
B18	2.98	85	9.7	0.1	0.6	0	2.2	1.6	0.8
B14	2.66	77.9	4.1	2.7	3.6	10.1	0	1.3	0.3
B11	2.66	86.3	5.8	1.4	1.1	4.6	0	0.3	0.5
B7	2.79	79.3	4.8	2.9	3.9	7.5	0	1.3	0.3
B2	2.33	58.6	6.5	7.4	16.1	9.1	0	1.9	0.3

content is derived from the feldspathic-rich rocks of the Berry Formation and possibly the granites of the Lachlan Fold Belt that occur in the catchment of the Shoalhaven River.

Carbonates were almost absent in Seven Mile Beach-Comerong Island sands (B33, B27, B22 and B18), but constitute a significant portion (16.4%) of sample B14, located at Culburra, as well as, in Warrain-Currarong samples, where abundance increased southwards, from 7.1% at B11 to 32.6% at B2. Aragonite was the most abundant of the carbonates, and its abundance in Culburra and Warrain-Currarong samples can be attributed to the biogenic skeletal remains of marine organisms, including gastropods and bivalves, that inhabit the submerged rock reefs offshore of Beecroft Peninsula.

The Shoalhaven River carries a substantial mud component, and the extensive estuarine plains that underlie the landward portion of the Shoalhaven compartment shown in Fig. 1 are predominantly muddy. These fine sediments are carried out to sea during major flood events when the beach-berm is breached and the mouth is open, as evident from sediment plumes that can be seen on satellite imagery. Mud is a negligible component of the beach sands (Fig. 3f), and clay minerals were present in only minor amounts (Table 3).

Storm modelling

Wave-refraction diagrams for the nine largest storms of 2014–2015 (Table 2) are shown in Fig. 4. A clear northwards increase in wave height is apparent, caused by the sheltering that Beecroft Peninsula provides for the southern beaches when storms are from the south and southeast. For example, the storm of April/2014 (4.6 m/11.4 s/131°) produced higher waves in the northern half of Seven Mile Beach-Comerong Island than in the southern half of the beach and at Culburra (Fig. 4a).

The increase in wave heights reaching the northern coastline is even more apparent in the case of the storm of May/2014 (4.6 m/14.8 s/152°), partly because it orignaed from a more southerly direction (Fig. 4b). A similar wave-propagation pattern was typical of the other storms which also had a more southerly origin (Fig. 4c-g).

The storms of August/2014 and the last one of April/2015, were the second and third most powerful storms, and generated the highest significant waves towards the northern end of Seven Mile Beach (Fig. 4d and f). The highest waves of the southerly storms of July (4.6 m/10.3 s/189°) and August/2015 (4 m/13.8 s/185°) missed the study area and propagated further north. Waves refracted at Beecroft Peninsula, and also by the adjacent underwater rock reef known as Sir John Young Banks, resulted in decreasing wave heights around Comerong Island, Culburra and Warrain-Currarong beaches, whereas higher waves reached Gerroa at the northern end of Seven Mile Beach-Comerong Island (Fig. 4h and i).

Whereas these storms constitute the events that were most likely to shape the three beaches during the study period, they were not of sufficient magnitude to cause major erosion. A sequence of storms in 1974 casued widespread erosion along much of the NSW coast, from which it took months (or even years) to recover (Thom and Hall 1991). Another major storm occurred in June/2016, only a few months after the last of the beach surveys in this study. That storm resulted from an east coast low, but waves originated uncharacteristically from a more easterly direction than most storms, and resulted in significant erosion to the southern section of many beaches, including Collaroy Beach in Sydeny (Harley et al. 2017).

Beach profile envelopes

The profile envelopes, or swept prism, of the ten sites monitored with RTK-GPS are shown in Fig. 5. When the monitoring started (December/2013-January/2014; dashed black lines in Fig. 5), a small incipient foredune existed at SH1, a 1.2-m high scarp and a featureless gentle slope was observed at profile SH2, a 5-m high scarp and narrow subaerial beach existed at SH3, and the incipient foredune was approximately 4 m in elevation at SH4. At Culburra,

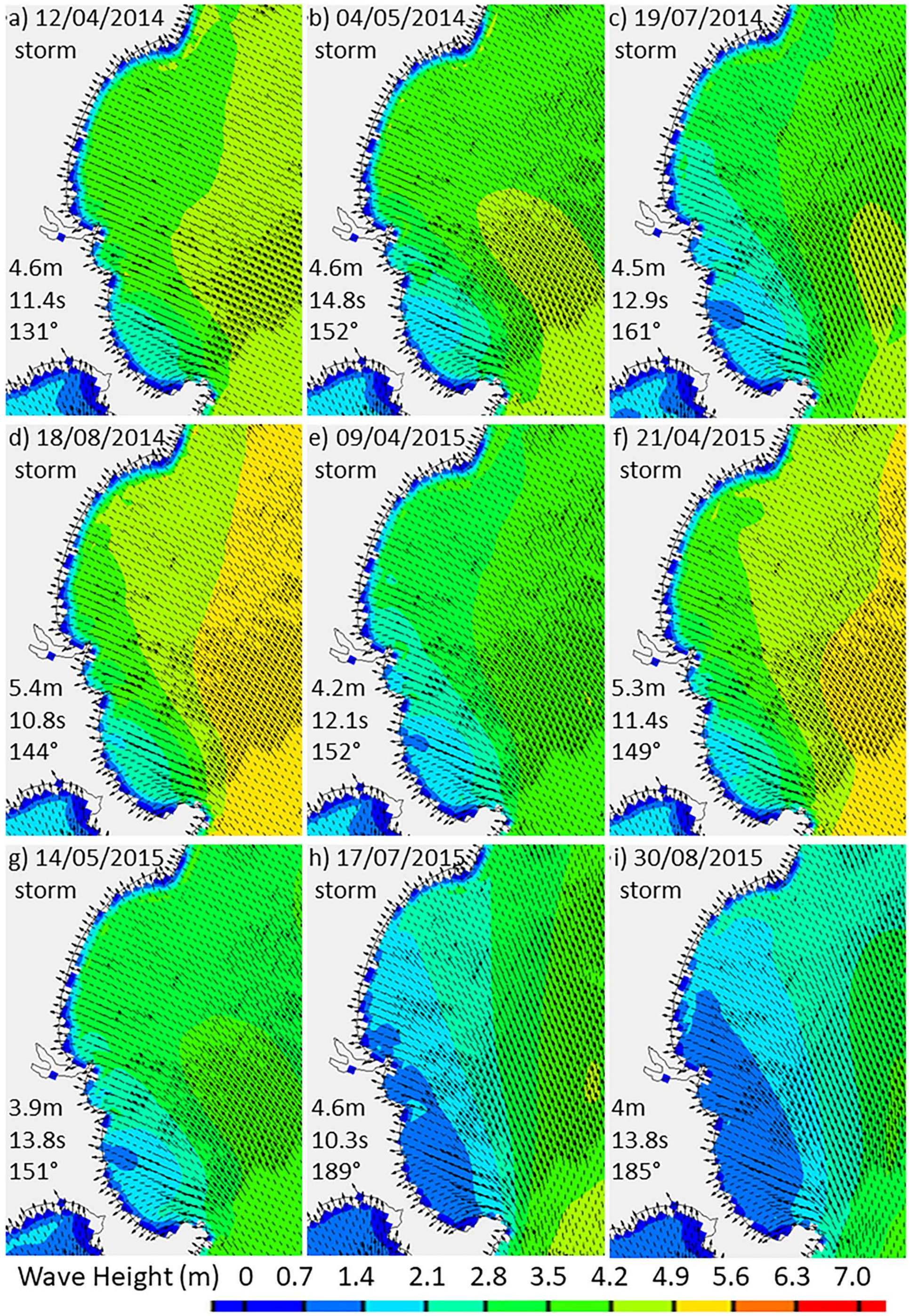

Fig. 4 Wave refraction diagrams modelled using STWAVE for the strongest storms of 2014 and 2015 listed in Table 2. Arrows indicate wave direction, whereas colours represent wave height

a 1.3-m high scarp and a narrow subaerial beach (< 40 m) was observed at CU1, a quite steep profile existed at CU2, and a small (1-m) scarp was found at CU3. The northern end of Warrain-Currarong (WA1) was quite steep, a continual slope seawards from the beach berm occurred at WA2, and a 25-m long gradual slope was observed at WA3.

By the time the monitoring finished (November/2015; full black lines in Fig. 5), the incipient dune had prograded slightly at SH1, considerable accretion had taken place at SH2, the shoreline had retreated and a much higher scarp was observed at SH3, and a vertical scarp occurred at SH4. At Culburra, sand accumulated in the foredune toe and overtopped the foredune crest at CU1 and overtopping had taken place to a lesser extent at CU2, whereas the scarp toe was filled in at CU3. The beach became much wider and a 2.5 m berm was observed at WA1, whereas the width increase was less pronounced at both WA2 and WA3.

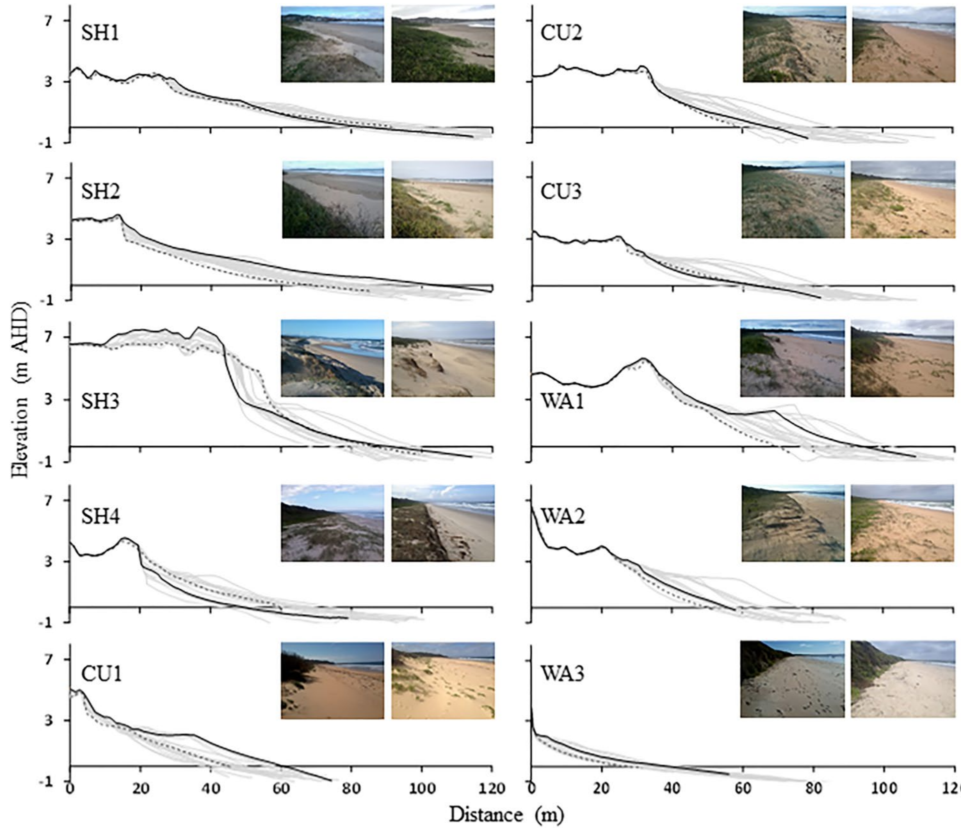

Fig. 5 Monthly morphological change experienced at Seven Mile Beach-Comerong Island (SH1-SH4), Culburra (CU1-CU3) and Warrain (WA1-WA3) between December/2013 and November/2015. Dashed and full black lines represent first and last surveys, respectively. Photographs taken looking towards the north show beach condition at the beginning and at the end of monitoring period. Additional photographs can be found in the Supplementary material. Location of profiles is shown in Fig. 1

Beach response to storm events

Beaches within the Shoalhaven compartment vary in beach state over time. Whereas the highest wave energy conditions and the most dissipative beach states occur at the northern end of Seven Mile Beach (SH1), the other beaches vary across intermediate beach states. The morphodynamic variability of these intermediate beaches contrasts with the lesser mobility associated with SH1 ($\sigma = 8.4$ m^3/m) and the modally reflective beach at WA3 ($\sigma = 6.9$ m^3/m). The intermediate beaches responded markedly to storm events, and were also characterised by rip circulation, which intensifies beach erosion and increases the susceptibility to erosion-accretion episodes (Short and Hesp 1982).

Beach surveys were undertaken simultaneously at monitored profiles on the three beaches relatively regularly over the 2-year period, whereas storms were irregular. Consequently, surveys were often several days, or even weeks, after any individual storm. This means that observed change could not always be attributed primarily to any one particular storm event. Nevertheless, the record of shoreline displacement (measured as monthly beach width deviation from the 2013–2015 mean position, Fig. 6; and monthly volumetric change (above 0 m AHD) relative to 2013–2015 mean, Fig. 7) indicate that the three beaches were behaving differently from each other, as well as varying along the length of each beach.

Beach volume increased the most over the two years at SH2, WA1 and CU1 (56.4, 54.5 and 39.5 m^3/m, respectively). CU2, WA2 and WA3 each exhibited a net gain of a similar volume (around 11 m^3/m), and SH1 gained approximately 3 m^3/m. A small net loss of approximately 1 m^3/m was observed at CU3, whereas SH3 and SH2 decreased by more than 23 m^3/m over the two-year period.

The greatest variability of profile volume was observed at WA1 ($\sigma = 20.4$ m^3/m), followed by SH3 ($\sigma = 18.7$ m^3/m), CU1 ($\sigma = 16.9$ m^3/m) and SH4 ($\sigma = 16.6$ m^3/m). The least variability was exhibited by WA3 ($\sigma = 6.9$ m^3/m), followed by SH1 ($\sigma = 8.4$ m^3/m). The first two storms of 2014 did not significantly impact the monitored profiles, apart from SH3 and SH4 which experienced a volume loss of less than 8 m^3/m. A large loss of volume, however, was observed at SH3 between the surveys conducted in May/2014 and July/2014. The storm that occurred a week after the July/2014 survey only impacted the beach at SH1, SH2 and SH4. All other profiles including SH3 experienced accretion.

The massive storm of 18/08/2014, which lasted more than two days with significant waves higher than 3 m, had a profound impact on the three beaches with volumetric losses

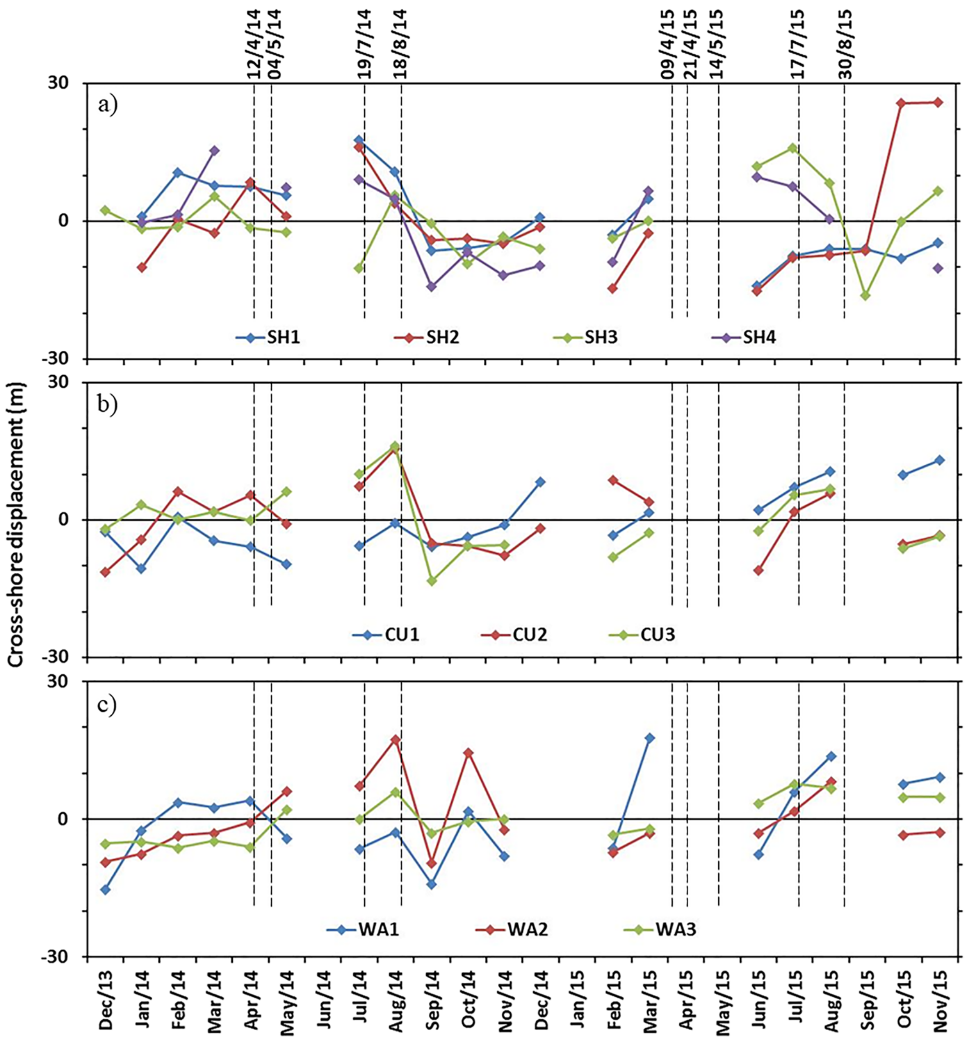

Fig. 6 Monthly beach width deviation from the 2013–2015 mean position for each profile line at Seven Mile Beach-Comerong Island (**a**), Culburra Beach (**b**) and Warrain-Currarong Beach (**c**). Vertical dashed lines indicate storms

occurring at all of them, especially at WA2 (-63 m^3/m), CU3 (-54 m^3/m), CU2 (-48 m^3/m) and SH4 (-44 m^3/m). As anticipated, all three beaches recovered during the six-month period between this massive storm and the first storm of 2015, despite some sporadic variability in volume.

A sequence of three storms occurred between April and May/2015. These mostly impacted profiles SH1, SH2, CU2 and WA1. The latter lost most of the volume it had gained over the summer (September to March) period (-42 m^3/m). Surprisingly, CU1 gained 16 m^3/m following the autumn storms (April/May). The southerly storm of July/2015 had a similar effect on each of the three beaches. The northernmost profile of each beach (SH1, CU1 and WA1) remained stable, profiles SH2, CU2 and WA2 accreted, and profiles SH3, CU3 and WA3 experienced a small loss, with SH4 exhibiting a greater loss of approximately − 10 m^3/m.

Flooding associated with the last storm of 2015 caused Shoalhaven City Council to open the river entrance at Shoalhaven Heads to prevent inundation of the Shoalhaven Heads settlement. This storm had considerable impact on the beaches, with a substantial loss of sand at SH3 (-65 m^3/m), and moderate loss at SH2. The immediate consequences of this storm at SH4 and the profiles on Culburra and Warrain-Currarong Beaches could not be assessed as it was not practicable to survey those sites.

The lack of synchronized behaviour for these three adjacent beaches, despite identical tides and similar grain sizes (medium to fine sand), indicates that not all embayed beaches within a secondary compartment behave in a similar manner. In the case of the Shoalhaven compartment, the intermittent delivery of sand from the Shoalhaven River has a local effect that influences the behaviour of the adjacent beach (Carvalho and Woodroffe 2014), but not the other beaches in the secondary compartment. Coastal managers will need to consider the individualistic behaviour that may occur at the tertiary-compartment (individual beach) scale.

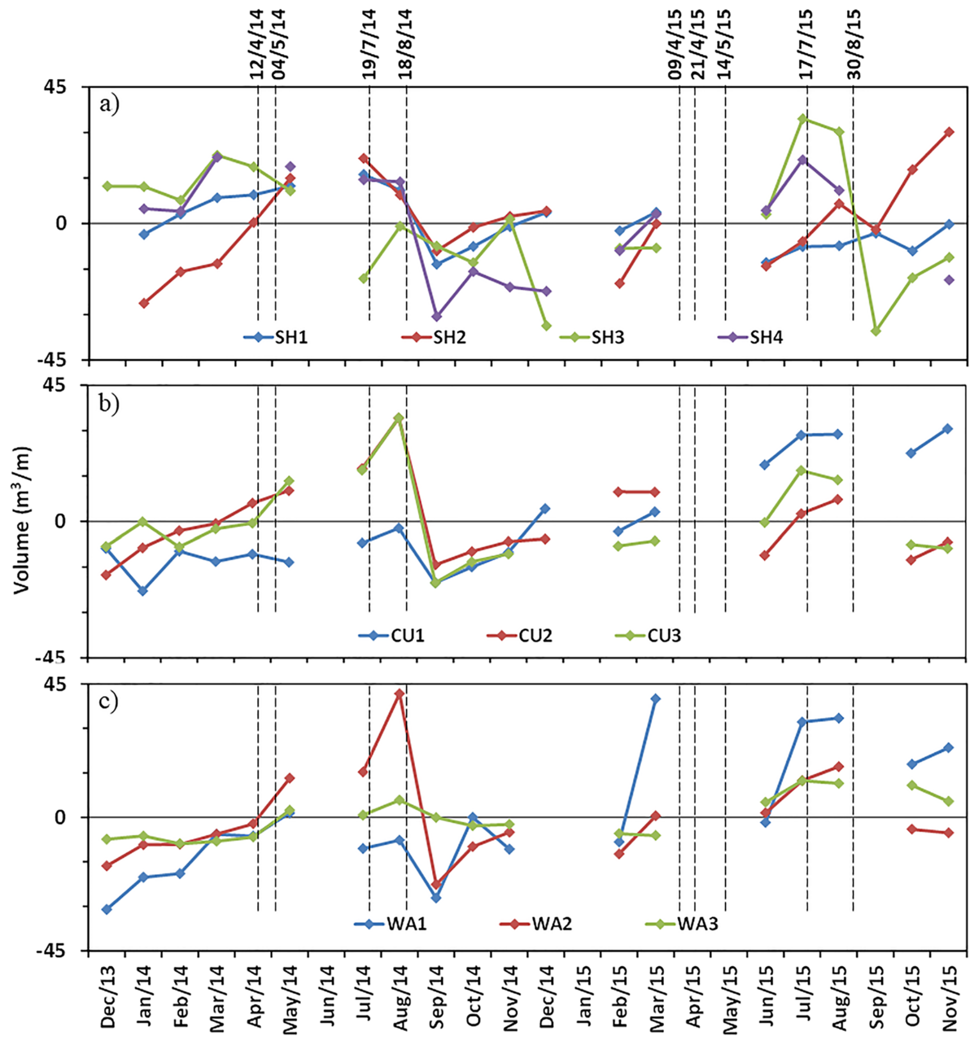

Fig. 7 Monthly beach profile volume change (above 0 m AHD) relative to 2013–2015 mean at Seven Mile Beach-Comerong Island (**a**), Culburra Beach (**b**) and Warrain-Currarong Beach (**c**). Vertical dashed lines indicate storms

Discussion

The long-term beach surveys that have been continued at Narrabeen-Collaroy Beach (in Sydney to the north of Shoalhaven) and Bengello Beach (at Moruya to the south) provide an invaluable insight into beach behaviour in southern NSW, and have served as the catalyst for beach morphodynamics in Australia and internationally (Short 2012). Whereas this body of understanding forms a fundamental basis for managing beaches throughout southern NSW, the hierarchical compartment approach provides a framework within which to consider the individual tertiary compartments and their separate behaviours, which may differ slightly from compartment to compartment. Below we consider the issue of beach orientation on the one hand, and that of the role of sediment supply on the other.

Beach orientation

The long-term studies at Narrabeen-Collaroy Beach indicate beach rotation whereby beach volume at either end responds to oceanographic conditions, particularly wave direction, associated with ENSO (Goodwin et al. 2020). Similar rotational behaviour has been observed on other beaches in southern NSW (Short et al. 2014), but it is not clear how widespread this can be, and to what extent other unmonitored beaches may respond similarly to ENSO conditions.

The four beach profiles at Seven Mile Beach-Comerong Island had also been monitored during the two years prior to our study. During that previous 2011–2012 monitoring period a trend had become apparent with erosion at the northern end of the beach and accretion at the southern end that could have been inferred to be a component of rotational behaviour (Carvalho et al. 2015). However, no such synchronized behaviour in terms of linear trend in shoreline position was observed during the 2013–2015 period reported in this study.

Beach width deviations from the mean position for the 2013–2015 period at each survey line and beach volume estimates (Figs. 6 and 7) do not reveal any consistent signs of beach rotation. The observations at Seven Mile Beach-Comerong Island do not show continuation of the trend inferred from the 2011–2012 surveys (of accretion at the southern end).

There was little consistency in trend for Culburra Beach and Warrain-Currarong Beach; in any case the shorter period of observation of only two years is insufficient to detect ENSO-related oscillatory behaviour or establish a relationship with wave climate and the Southern Oscillation Index (SOI), such as demonstrated for Narrabeen-Collaroy Beach (Ranasinghe et al. 2004; Short and Trembanis 2004; Harley et al. 2011). The protrusion of Beecroft Peninsula, which is such a prominent headland feature, represents a significant obstruction to southerly and southeasterly storms, and explains why these southern beaches behave differently from less sheltered beaches elsewhere on the NSW coast.

Sediment supply

We have demonstrated that the Shoalhaven River delivers sediment to the Shoalhaven coastal compartment when the mouth is open. Bathymetric surveys of the shoreface between 1981 and 2006 indicate that, after breaching of the mouth at Shoalhaven Heads, sand was deposited in a broad crescentic river-mouth bar (Carvalho and Woodroffe 2021). Much of that sand has been re-distributed along the shoreline, continuing the trend of coastal progradation that has been detected from photogrammetric studies of the beach. A conservative estimate implies that at least 1,065,000 m^3 of sand was delivered in that 25-year period. During the period of our monitoring it seems likely that opening of the river mouth at Shoalhaven Heads in June/2013 and August/2015 will have resulted in the delivery of sand to the coast, and consequently affected the pattern of behaviour of the adjacent beach.

Indicating that the river delivers sand to the coast may not seem to be remarkable, as such transfer is clearly a fundamental feature of the global sediment cycle (Syvitski et al. 2022). Rivers can provide substantial sediment inputs into coastal compartments that increase the sediment budget and are redistributed along the shoreline (Phillips and Slattery 2006; Warrick 2020). At a global scale this delivery represents the major portion of the global sediment budget (Syvitski et al. 2022), and the transport of material from large catchments, such as that of the Amazon River, contributes to coastline adjustments along hundreds of kilometres of adjacent shorelines (Nittrouer et al. 2021).

There have even been attempts to quantify the extent of the fluvial contribution to shoreline change across the world, using satellite products and a variety of re-analysis products (Almar et al. 2023). However, our short-term study of the morphodynamic adjustments of these three tertiary compartments demonstrates the complexity of changes at sub-annual scale. Our results indicate the shortcomings of the global generalisations, such as those proposed by Almar et al. (2023); the southeastern coast of Australia is not river-dominated as their analysis implies. The gradual redistribution of sand following its intermittent delivery from the catchment is not yet amenable to simple modelling. There is considerable potential to capture the general trajectory of change using emerging coastal products such as CoastSat, as indicated above and as shown recently by Warrick et al. (2022). Nevertheless there remains a role for field-based surveys, designed at suitable spatial and temporal scales, to address particular management problems, and to validate the outcomes of broader initiatives to model past coastal change, with the ultimate aim of enabling more credible forecasts in future.

The majority of creeks and rivers along the NSW coast are not delivering sand to the shoreface at present. Instead, fluvial–derived sand is deposited in bay-head deltas within estuaries and coastal lagoons. The geomorphological evolution of these estuarine systems has been comprehensively described (Roy 1984, 1994), and only in the mature stages do river channels traverse the infilled estuarine plains and contribute sand to the coast. A majority of the 130 most important NSW coastal water bodies, have intermittently opening/closing entrances (Roy et al. 2001). Along the wave-dominated coast of NSW the early stages of estuarine infill commenced when the sea level reached close to its present level around 7,000 years ago. Incompletely filled estuaries are classified as wave-dominated estuaries, whereas those that have infilled the prior embayment are called wave-dominated deltas in a classification of coastal systems in Australia (Harris et al. 2002).

The Shoalhaven River is one example of a system that has transitioned from estuary to delta (Carvalho and Woodroffe 2020a). We demonstrate above that a fluvially-derived component can be detected within the sands on the Seven Mile Beach-Comerong Island tertiary compartment. Even the colour of the sand (as seen in Fig. 3) hints at the discrimination of the older well-reworked marine sands of the closed compartments of Culburra and Warrain-Currarong Beaches. The mineral composition and the angularity of individual quartz grains further support a river contribution to the sands of the northern tertiary compartment within the Shoalhaven secondary compartment.

Historically, short-lived breaching events that last less than a year before the closing of the entrance, such as the ones that occurred in 2015 (five months), 2013 (nine months), 1999 (three months) and 1998 (six months) discharge reduced amounts of sand that are mostly deposited in shallow water and are immediately available to be transported back to the shore. However, breaching events with large delivery of sediments to the nearshore can have consequences for shoreline dynamics for decades.

These sedimentological clues even provide a basis for estimating when the estuary had largely infilled and the contribution of fluvially-derived sand to the coast became substantial. Although the presence of angular river sand associated with radiocarbon-dated shells had been interpreted to indicate that fluvial sand was reaching the coast by 6,000 years BP (Young et al. 1996), the estuary continued to sequester considerable sediment for the following 3,000 years (Umitsu et al. 2001). The sequence of ridges that form the prograded barrier behind Seven Mile Beach contain well-rounded quartz sand as would be anticipated as a consequence of the inter-connection between the sandy shoreface and the foredune ridges. However, progradation of the ridge sequence accelerated and a fluvial component became more conspicuous after about 2,500 years BP (Carvalho et al. 2019).

Although there are many aspects of beach behaviour that apply at a regional scale, other local factors such as sediment input and output play an important role in shoreline variability at a local level. In the case of the Shoalhaven secondary compartment, sediment supply driven by floods and intermittent opening of the river mouth needs to be a consideration in managing the northernmost tertiary compartment. The discontinuous process of fluvial sediment supply to the beach (Gordon et al. 1980), the time it takes for the redistribution of sediments in the nearshore, and the partial return of sediment to recompose the beach berm, have a significant role in beach behaviour. Five months prior to the beginning of the monitoring period (December 2013), the artificial opening of the river entrance at Shoalhaven Heads resulted in the delivery of fluvial sediments to the nearshore. Nine months after the breaching event, partial return of sand from the vicinities of the mouth and the nearshore filled the opening. This eroded the adjacent shoreline and increased the existing scarp at SH3 during the first five months of 2014. The residual sediments that remained in the nearshore formed a storage of sand that would later be transported alongshore by wave action and eventually be reworked onto the beach.

These sediment transport pathways need to be considered when addressing erosion threats, such as that posed to the Shoalhaven Heads surf-life saving club facilities. Here beach scraping (mechanical movement of sand from the lower part of the beach onto the higher part of the beach/dune) has been necessary to reduce hazardous erosional scarp, that has been up to 4 m high in front of the clubhouse.

Monitoring beaches for coastal management

Regular beach surveys have been conducted at key sites on the coast of southern NSW for at least the past five decades and they continue to provide information on ongoing changes to those beaches studied, as well as insights into regional beach behaviour. Further physical surveys of this type, as undertaken over the two-year period in this study, will continue to be undertaken, especially in the context of managing specific issues (e.g. Gangaiya et al. 2017).

Such standard survey protocols have been supplemented by other techniques. Aerial photography and photogrammetry have proved useful over decades for examining behaviour on other beaches (Hanslow 2007). More recently, sophisticated techniques have been developed to derive indicators of shoreline position from satellite imagery, with products such as CoastSat (developed at the Water Resources Laboratory, UNSW, Vos 2019), and the Digital Earth Australia (DEA) "Coastlines" (produced by Geoscience Australia, Bishop-Taylor et al. 2021).

These approaches enable broad assessment of shoreline change on a national, and increasingly at an international, scale, and will be especially important in considering the response of shorelines to sea-level rise (Nanson et al. 2022; Short 2022; Vos et al. 2023). At this stage these approaches do not give the same degree of information as on-ground surveys. Satellite-derived information have a much coarser spatial resolution than our surveys and do not capture the morphology of the beach and the presence/absence of berms and erosional scarp of foredune. Time-series of shoreline change extracted with CoastSat may contain a tidal bias (Vos et al. 2019), whereas the DEA "Coastlines" are an average annual product (Bishop-Taylor et al. 2021) that do not capture the temporal variability and the seasonal effects observed through our monthly surveys. Comparison of our displacement results for SH2, SH3, CU2, CU3 and WA2 (Fig. 6) appears to agree with the rate of coastal change observed between 1988 and 2021 using DEA "Coastlines". However, significant differences were observed at SH1, CU1 and WA1, for instance.

Increasingly, other approaches to beach monitoring are becoming available, such as fixed camera systems (e.g. Harley et al. 2015b), and surveys using drones (e.g. Turner et al. 2016; Pucino et al. 2021). The challenge for coastal managers will be deciding which tools or survey methodologies best meet their requirements, and those decisions usually depend upon what specific goals are to be met. As the opportunities diversify, making those decisions becomes harder, and traditional survey approaches that can be carried out in-house are likely to persist for some time yet.

Meanwhile, the sharing of ideas and the inter-comparison of results offer an integrated way of undertaking coastal management programs. The hierarchy of coastal compartments is a framework within which observations about particular beaches can be organised, and behavioural characteristics rationalised.

Conclusion

The contrast in grain size, sorting, shape, colour and mineralogy suggests different provenances for the modern beach sands of the Shoalhaven coastal compartment. Sands of fluvial origin dominate Seven Mile Beach-Comerong Island, whereas reworked shoreface sands constitute the beaches of Culburra Beach and most of Warrain-Currarong Beach. These facts suggest that the sediment budget of these closed beaches are independent from each other. Our analyses suggest that there is little if any sand bypassed between Comerong Island and Culburra Beach, and that the southern beaches are closed tertiary compartments. The carbonate content is likely to be associated with organisms on the extensive rocky reefs of Beecroft Peninsula, and the contribution their skeletal remains make to sediments on the nearby beach.

This study investigated the morphological change of all three beaches within a secondary level compartment in southeast Australia. The adjacent beaches are exposed to the same tidal and deep-water regional-scale wave and climate forcing, despite having differences in shallow-water wave energy and beach states. The envelopes of beach profiles monitored over two years at a total of ten different sites indicate that the beaches have shown no synchronized behaviour in terms of linear trend in shoreline position as might have been expected if there was a regional pattern of beach rotation. Adjacent embayed beaches along the coast do not necessarily behave in a similar manner, and attempts to establish a broad monitoring program using beaches representative of regional behaviour will need to take into account sediment input. A coastal compartment approach provides a hierarchical scheme within which broad characteristics at the secondary compartment level can subsequently be considered at a more local scale, in order to establish which parameters constrain the behavior of individual beaches. Such an approach could be used to assess future response to sea-level rise, whereby each compartment may occur in a broad regional context, but be subject to factors that apply specifically at the more local level.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11852-023-00984-6.

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Data availability The beach profile data used for this research are permanently available in a public repository (Mendeley Data) https://doi.org/10.17632/shwpvfb9sr.1. Surficial sediment data for Seven Mile Beach-Comerong Island is publicly available at https://doi.org/10.1016/j.dib.2020.105813. The remaining datasets, processed files and model outputs are available from the corresponding author upon reasonable request.

Declarations

The authors have no relevant financial or non-financial interests to disclose. CDW is part of the JCCPM's editorial board.

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