Journal of Coastal Conservation (2022) 26: 21
https://doi.org/10.1007/s11852-022-00867-2

# Sediment dynamics at different timescales on an embayed coast in southeastern Australia

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Received: 25 August 2021 / Revised: 22 February 2022 / Accepted: 23 April 2022 / Published online: 18 May 2022

## Abstract

The concept of coastal sediment compartments has recently been adopted at a national scale in Australia to better understand sediment and shoreline dynamics and to underpin management of future shoreline behaviour in response to impacts of climate change. Geomorphological studies in southern NSW have provided a foundation for development of conceptual models of estuary and sandy barrier evolution. Geochronological reconstructions using radiocarbon, optically-stimulated luminescence, and other dating techniques, reviewed in this paper, demonstrate that adjacent compartments are at successive stages. Three compartments, Illawarra, Shoalhaven and Moruya, are compared, each with different catchment characteristics and different levels of human intervention. Landform change and sediment accumulation at millennial timescales enable estimates of past sediment accretion (vertical accumulation) and horizontal displacement of shorelines (particularly progradation), as a first step towards quantifying volumetric changes of morphology. Lake Illawarra is a barrier estuary at an early stage of infill, but land-use change, urbanisation, and engineering structures at the entrance have accelerated rates of sediment accumulation. The Shoalhaven River has infilled its estuary and delivers sand to the coast. It has been subject to several conspicuous anthropogenic interventions. At Moruya, ongoing supply of sand, primarily from offshore rather than from the catchment, has resulted in beach-ridge plains (strandplains) with changes in their alongshore inter-connectivity driven by differential embayment infilling. Millennial-scale geomorphology indicates landform change providing a means to determine natural trajectories of sediment transfer. However, variability is apparent at century and decadal timescales, compounded by various anthropogenic interventions. Disentangling natural and anthropogenic influences will be necessary to provide greater confidence in estimating past and present sediment budgets. Assessing sand sources and transport rates is important in relation to engineering interventions at entrances, and long-term resilience of coastal habitats. Such issues are the focus of coastal management programs, and this synthesis emphasises the relevance of a sediment budget approach to understand contemporary sediment pathways and provide an indication of future response to engineering interventions and sensitivity to climate change.

**Keywords** Coastal sediment compartment · Sediment budget · Morphodynamics · Barrier estuary · Anthropogenic impacts · Southeast Australia

## Introduction

Coasts are highly dynamic environments, responding to changes in sediment delivery and oceanographic processes

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that shape beaches. Coastal landforms result from supply of sediment, its transport, and subsequent deposition. The concept of a sediment budget, based on conservation of mass, has been widely used in the US (Bowen and Inman 1966; Rosati 2005). It forms the basis of shoreline management plans in England and Wales (Motyka and Brampton 1993; Cooper et al. 2002). A similar approach was first applied to the Australian coast by Davies (1974), and provides a framework for coastal planning and management.

The embayed coast of southern New South Wales (NSW) contains a sequence of coastal waterways, many of which require management entailing engineered interventions to improve navigation or to address environmental concerns, such as perceived poor water quality. These interventions can lead to ongoing geomorphological, hydrodynamic, water quality and ecological issues, as well as alterations to the prevailing sediment transport pathways (Ferguson et al. 2021). This reinforces the importance of understanding sediment sources and sinks and how they impact estuary environments. In this paper, we examine three sediment compartments in which it has been found necessary to manage or constrain entrances including through construction of training walls. We consider the extent to which Holocene depositional history can provide insights into sediment movement with a view to better understanding what is happening today to landforms and habitats, with the broader goal of anticipating, and managing, what may happen in the future.

A hierarchical system of sediment compartments, bounded by prominent changes in orientation, geology or topography, has recently been described around Australia (Thom et al. 2018; Short 2020). The compartment approach, first undertaken in Western Australia, was designed for management and planning purposes (Eliot et al. 2011, 2013; Stul et al. 2007, 2015). In New South Wales (NSW), the *Coastal Management Act*, passed in 2016, recommended that coastal management programs use the sediment compartment approach. Forty-six secondary sediment compartments were identified in which sediment sources, sinks and pathways were likely to be different, in some cases transcending jurisdictional boundaries. Within the secondary compartments there are generally several smaller compartments, called tertiary compartments, often corresponding to individual beaches. Understanding sediment transfers within such compartments should enable better coastal management (Carvalho and Woodroffe 2014; Short and Thom 2018).

On embayed coasts, a beach occupying the embayment between two headlands may be subject to net gains (positive) or losses (negative) of sand over time. Many compartments contain an estuary; estuaries are typically a trap for sediment derived from their catchments, as well as sand carried into them from seaward as a result of waves and tidal currents. When an estuary has been infilled, it may transition into a delta where sediment is delivered directly to the coast during major floods (Carvalho and Woodroffe 2020). Sand may also be supplied from alongshore transport into compartments, including headland bypassing, augmenting onshore supply from the shoreface or inner continental shelf. Conversely, sand may be lost offshore or alongshore, or by landwards transport into dunes (Kinsela et al. 2017; Thom et al. 2018). Both open sandy coasts and adjacent estuaries have been extensively studied on the NSW coast (Thom et al. 1981; Chapman et al. 1982; Roy et al. 2001), but sediment transport within and between them has received less attention despite its relevance to the sustainability of habitats, and where engineering structures have been considered necessary.

It is challenging to determine a sediment budget for a section of coast, because rates of process operation vary geographically, and also change over time. Physical processes associated with waves and tides occur at an *instantaneous* timescale, but the landforms that result are intermittently disrupted at an *event* timescale (Cowell and Thom 1994). For example, a berm that is built by swell action on a beach is reshaped by an individual storm event that erodes the beachface and foredune. These, in turn, may undergo gradual recovery, until returning to conditions comparable to those prior to the event. A record of longer-term coastal behaviour, at the *geological* or millennial timescale, may be preserved, especially where the sediment budget is positive and the beach is backed by a sequence of beach ridges (also called a strandplain), marking former shoreline positions. There is a fourth timescale, spanning decades to centuries, referred to here as *historical*. It involves coastal change on timescales that are most relevant to adaptation planning, conservation, and engineering works in the context of future climate change and anthropogenic pressures.

Depositional coastal landforms often comprise an incomplete aggregation of the sedimentary outcomes of numerous events. Understanding adjustments over longer timescales can provide a basis for interpreting shorter-term variability. Geomorphological studies that reconstruct sedimentary history on millennial scales can be a guide to rates of process operation, as well as future behaviour of coastal systems (Woodroffe and Murray-Wallace 2012). Forecasting remains especially challenging at the decade-to-century timescale, but an indication of the trend or trajectory in sediment budget may ultimately determine whether shorelines recede, are stable, or prograde. The sediment budget of compartments is highly variable and can switch from positive to negative, either episodically or in response to a long-term change in conditions.

This paper examines variability within several sediment compartments along the south coast of NSW. It reviews the depositional chronology for the past few millennia of the Holocene, and places reconstructions of past shorelines in the context of a coastal sediment budget. It explores sources, transfer, and deposition of sand at millennial, century, and decadal timescales, examining the inferred pathways and sediment transfers between estuaries and adjacent coast. We consider the extent to which human interventions have modified rates of geomorphological process operation. This longer-term perspective can provide insights into how systems have behaved, which may assist managers to better forecast the consequences of engineering works, and planners to prepare for likely future adjustment of coastal landforms to changes in climate and sea level.

## The New South Wales coast in a morphodynamic context

The NSW coastline extends for 1600 km, and 755 sandy beaches have been described along its length (Short 2007). The south coast of NSW, backed by the eastern highlands, is drained by a sequence of relatively short and steep rivers. The coast is exposed to considerable wave energy with little attenuation across a relatively narrow continental shelf, and has a maximum tidal range of < 2 m. Wave buoys have been in operation since 1974, recording dominant waves from the southeast, with more easterly and northeasterly waves in summer (December – March) (Mortlock and Goodwin 2015a, b). Beaches are periodically eroded by storm events with significant wave heights up to 9 m, and surges that reach 0.5 m or more (Kumbier et al. 2018). Considerable volumes of medium to fine-grained, quartz-rich sand occur in water depths of 20–60 m on the inner continental shelf (Boyd et al. 2004; Roy 2006). Alongshore transport northwards, presumably less impeded when sea level was lower, has contributed to formation of several large sand islands in southern Queensland (Short 2010), and northward longshore transport continues in northern NSW (Goodwin et al. 2020). As the sea rose, these sands were reworked landwards forming sandy barriers and mainland beaches that characterise the numerous embayments.

Sea level reached its present level around Australia in the mid Holocene at the end of the postglacial marine transgression (Thom and Roy 1985). For the past ~ 7,000 years, sea level has been relatively close to, and perhaps slightly above, its present elevation (Sloss et al. 2007; Dougherty et al. 2019). The coast of NSW has played a disproportionate role in the development of coastal morphodynamic concepts (Wright and Thom 1977), particularly conceptual models of estuarine evolution (Fig. 1) and sandy barrier formation (comprising beach and dune environments), during relatively stable sea level (Fig. 2).

## Estuarine morphodynamics

Rivers in southeast Australia deliver sediment from their steep catchments, with adjacent estuaries and coastal lakes at different stages of infill (Roy 1984). Figure 1 provides a synthesis of these different estuarine stages; these are linked with factors that are important in addressing coastal management issues, such as geomorphic properties, water quality attributes, and ecology (Roy et al. 2001). The work of Roy and others has demonstrated how underlying geological and geomorphic controls affect other environmental parameters, such as salinity and sediment type, and are associated with ecological distributions, species richness, and even fisheries catch.

Environments of deposition within each type of estuary form dynamic elements that can be modified by human activities, including river flows from catchments, land-use practices within the estuary itself, and from interventions affecting shoreline sediment flows within entrance channels and adjoining sediment compartments. The three sediment compartments selected for study in this paper, while reflecting some differences in geomorphic history, nonetheless, offer insights into how an understanding of that history and ongoing processes within their sediment compartments can assist in forecasting longer term changes in estuary condition.

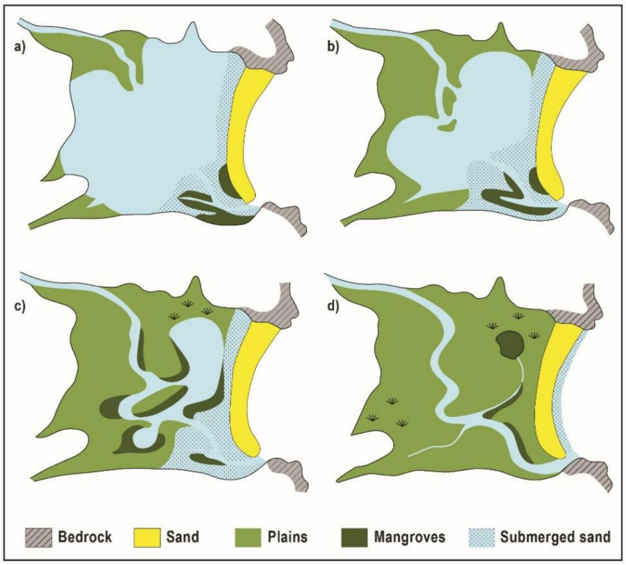

**Fig. 1** A schematic representation of the stages of infill of a barrier estuary, and its adjacent tertiary sediment compartment (based on Roy 1984). Individual estuaries along the NSW coast are presently at different stages, and chronostratigraphic studies indicate that estuaries evolve through these successive stages as they infill

When a river mouth is occluded by a sandy barrier, a broad coastal waterway, called a barrier estuary, is formed (Fig. 1a). Powerful swell waves can build a berm that closes the entrance, forming saline coastal lagoons (also referred to as ICOLLs, intermittently closed and open lakes and lagoons). Such estuaries are a sink for fluvially-derived sediment as well as quartz sands transported through the entrance by tidal processes from seaward, and infill progressively over time (Fig. 1b,c). Some rivers, principally those that drain the largest catchments, have infilled their estuaries entirely (Fig. 1d); these are termed a mature riverine estuary by Roy et al. (2001), and are considered deltas in a classification of Australian coastal waterways by Harris et al. (2002). At these locations, there may be episodic delivery of fluvial sand to the nearshore, nourishing adjacent beaches. Navigation, and more recently other environmental concerns, have led to past dredging and construction of engineered training walls at the entrance to several of these coastal waterways.

## Sand barrier morphodynamics

The onshore movement of sand over past millennia has led to development of several types of barrier shown in Fig. 2. A plentiful supply of sand from offshore can be inferred where there are prograded barriers (Fig. 2a), or transgressive dune barriers (Fig. 2d), in some cases augmented by fluvially-derived sediments at the mouths of those rivers that do supply sand to the coast (as opposed to those that are still infilling their estuaries). A single stationary barrier occurs in other places, often impounding an estuary or lagoon (Fig. 2b); where there is insufficient sand, a receded barrier may occur, overlying estuarine muds that can be exposed on the beach during exceptional storms (Fig. 2c). Shelf sand bodies occur offshore on predominantly rocky shorelines without suitable embayments for beach accumulation (Roy et al. 1994).

Studies along this coastline, including two of the longest records of beach monitoring anywhere in the world, have shown how beaches transition across a spectrum of beach states from dissipative to reflective in response to ambient and antecedent wave conditions Short and Wright 1981; Wright and Short 1984; Wright and Short 1984; Short 2012). Storms erode beaches and deposit sand in the nearshore, but beaches generally recover in subsequent weeks (Harley et al. 2016, 2017). The behaviour of Narrabeen-Collaroy Beach in northern Sydney has been recorded since 1976 (Short 2012; Turner et al. 2016), providing insights into rotation of beach orientation in response to regional climate variation associated with El Niño-Southern Oscillation phenomena (Ranasinghe et al. 2004; Harley et al. 2015). Beach surveys, discussed further below, were commenced in 1972 on Bengello Beach near Moruya, 250 km south of Sydney (Thom and Hall 1991; McLean and Shen 2006).

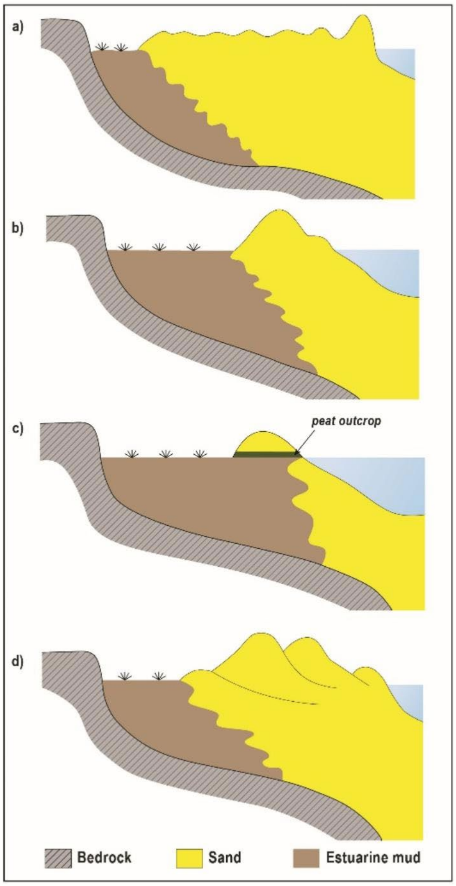

**Fig. 2** Schematic illustration of four of the principal sand barrier types along the NSW coast, (a) Prograded barrier (or strandplain), (b) Stationary barrier, (c) Receded barrier, and (d) Transgressive dune barrier (after Chapman et al. 1982)

## Coastal sediment compartments in southern NSW

Headlands mark boundaries of many compartments in southern NSW, reducing the extent to which sand moves from one compartment to another. Long-term trajectories of sediment deposition are preserved in the stratigraphy of coastal landforms, providing indications of past rates of supply (Cowell et al. 2003a, b; Goodwin et al. 2006), and can form the basis for models simulating coastal behaviour within the constraints of regional boundary conditions (Cowell and Kinsela 2019). The three secondary compartments considered in this paper are shown in Fig. 3.

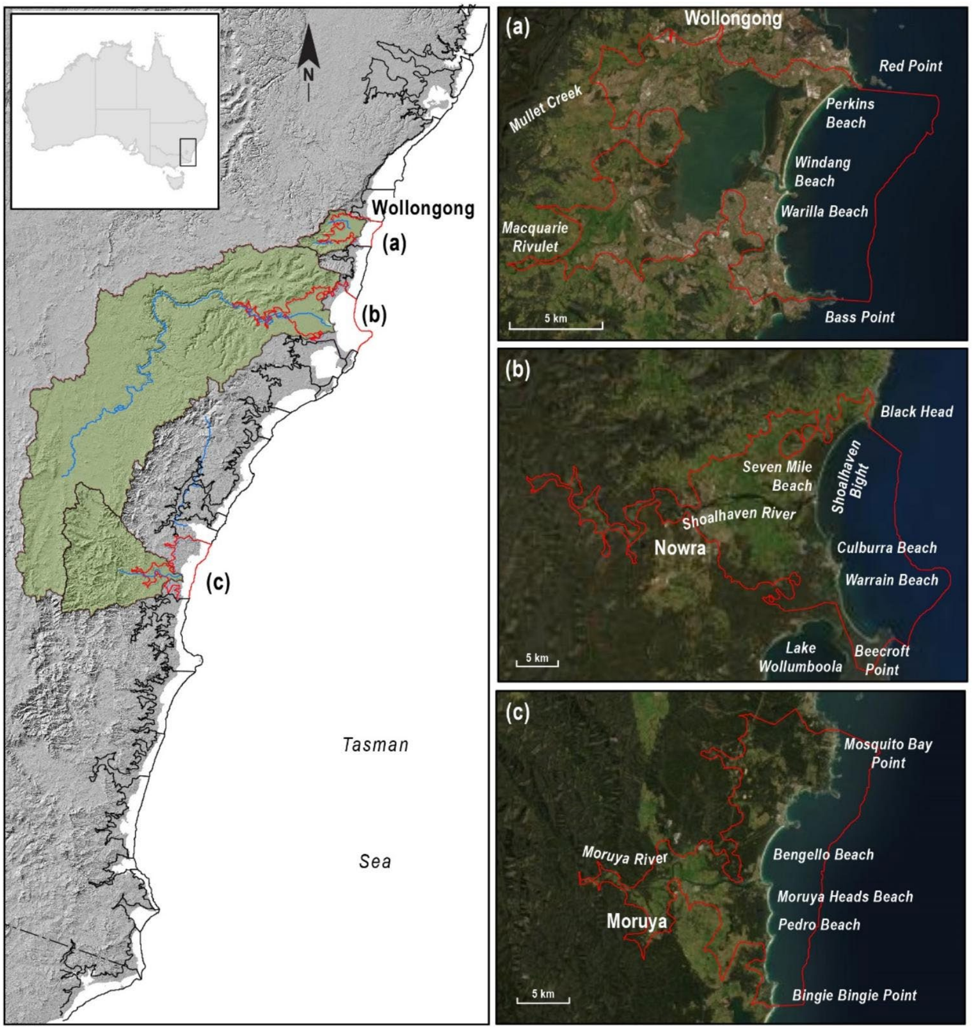

**Fig. 3** The south coast of NSW and location of selected compartments (these are secondary compartments delimited by the 50 m isobath and the 25 m contour as outlined by McPherson et al. 2015). (a) The Illawarra (south) compartment containing Lake Illawarra, (b) the Shoalhaven River compartment at Nowra, and (c) the Broulee compartment at Moruya

## Lake Illawarra

Lake Illawarra is a barrier estuary (Sloss et al, 2007) at a relatively early stage of infill (a in Fig. 1). It lies in the northernmost compartment, which is designated the Illawarra (south) compartment (NSW02.04.03) in the Geoscience Australia compilation, and spans from Red Point to Bass Point (McPherson et al. 2015). The lake is impounded by the Windang barrier (comprising Perkins and Windang Beaches), an episodic transgressive dune barrier (d in Fig. 2) where beach and nearshore sands are partly, or completely, covered by dunes (Hesp 1993). The dunes experienced periodic sand drift into the neighbouring suburbs prior to stabilisation with vegetation several decades ago, and have also been a source for past sand mining. Lake Illawarra has a surface area of 35 km$^2$ and an average depth of ~2 m. It has a catchment of ~238 km$^2$; Mullet Creek to the north drains 75 km$^2$ and Macquarie Rivulet drains 110 km$^2$. Warilla Beach south of the entrance to Lake Illawarra, also subjected to sand mining in the past, was the focus of repeat surveys at weekly to monthly intervals, which revealed the periodicity of beach behaviour on this wave-dominated coast (Eliot and Clarke 1982; Clarke and Eliot 1982). Construction of housing on the foredune has necessitated seawall protection at the southern end of Warilla Beach. Engineering works have recently been undertaken at the entrance to Lake Illawarra to keep it permanently open to the sea, emphasising the need for a clearer understanding of the respective sediment budgets of the estuary and its adjacent beaches.

Lake Illawarra is an example of a waterway that falls within two local government jurisdictions, Wollongong City Council and Shellharbour City Council. In 1987, the Lake Illawarra Authority Act established the Lake Illawarra Authority, which from 1988 to 2014 managed a series of environmental concerns relating to the lake, involving foreshore remediation, gross pollutant traps, artificial wetlands, and concerns about water quality (Morrison and West 2004). The entrance channel to the lake had a history of change, sometimes connected to Perkins/Windang Beach to the north and sometimes connected to Warilla Beach to the south, according to the orientation of a tombolo attached to Windang Island. At other times, the entrance closed naturally as a consequence of swell processes. In an effort to improve water quality and maintain a connection between the lake and the open sea, a rock wall was constructed on the southern side of the entrance in 2001. Various training wall configurations were considered, and hydrodynamic modelling indicated that these would have differing impacts on flows and sediment scouring in the channel (Treloar et al. 2004). Finally, twin entrance walls were completed in 2007, with dredging of sand from the channel (that was used to nourish Warilla Beach).

### Shoalhaven River

The Shoalhaven River compartment (NSW02.04.05) occupies Shoalhaven Bight, between Black Head in the north and Beecroft Point in the south. The Shoalhaven River drains one of the largest catchments in southern NSW (7,250 $km^2$), and has largely infilled the former barrier estuary (d in Fig. 1), which now comprises extensive floodplains (Thom et al. 1981; Roy 1994). Recent studies show that fluvially-derived sand is intermittently delivered to the shoreface at Shoalhaven Heads during floods, contributing to Seven Mile Beach to the north (Carvalho et al. 2019), supplementing the sequence of beach ridges that form the adjacent prograded barrier (a in Fig. 2). Shoals at the river mouth made navigation treacherous, and a local landowner, Alexander Berry, had convicts excavate a channel in 1822 to the smaller Crookhaven River. The route reoccupied an earlier course of the river, but Berrys Canal, has continued to widen (Carvalho and Woodroffe 2020). The channel required dredging in the late 19th century with a seawall constructed on the northern side of Crookhaven Heads between 1902 and 1908 This was later extended to form the present training wall between 1909 and 1912 (Coltheart 1997). The Shoalhaven River now drains to the ocean at Crookhaven Heads, except during major flood events when it breaches its former mouth, which remains open until the berm is rebuilt by sand moved by the persistent swell. In contrast to Seven Mile Beach, Culburra Beach to the south of the river has been classified as a receded barrier (c in Fig. 2) and has undergone a history of gradual recession, whereas Warrain Beach, occluding the intermittently open Lake Wollumboola (an ICOLL), appears to be a stationary barrier (b in Fig. 2).

### Moruya

The southernmost compartment occurs at Moruya (NSW 02.06.03; called Moruya River by Geoscience Australia, but also known as Broulee), extending from Mosquito Bay Point to Bingie Bingie Point. It contains several beaches separated by prominent headlands. The Moruya River (called the Deua River in its upper reaches) drains a catchment of 1424 $km^2$; it is considered to deliver little if any sediment to the coast (Hall 1981). The mouth of the river at Moruya was also important for shipping, and dredging and bank stabilisation was carried out in the late 19th century. A wall constructed in 1907 was partly degraded by subsidence in 1920, after which more substantial training walls were constructed in the following years using granite that was being quarried from this region for the construction of the Sydney Harbour bridge. Further extension of the training walls was undertaken between 1946 and 1954 (Coltheart 1997).

Bengello Beach has been the site of detailed beach and foredune surveys since 1972, as well as stratigraphic and geochronological studies of the prograded strandplain behind it (Thom et al. 1981). Moruya Heads Beach and Pedro Beach south of the river are backed by prograded barriers (a in Fig. 2); these record different sedimentary histories and inter-connectivity, described below.

## Holocene landform development and contemporary morphodynamics

Rivers and creeks deliver sediment from the relatively small but steep catchments that are characteristic of southeastern NSW. Average annual rainfall near the coast is ~ 1200 mm, increasing to > 1600 mm on higher ground, such as the escarpment crest of the Illawarra, but with considerable inter-annual variability (Carvalho and Woodroffe 2015).

Each of the Illawarra, Shoalhaven and Moruya sections of coast have been the focus of geomorphological studies since the 1970s. Collectively they have contributed to development of the conceptual models shown in Figs. 1 and 2. In this section the geomorphology of each is considered during mid Holocene, ~ 5,000 years ago, and aspects of the sediment budget examined on that millennial scale, and then contrasted with conditions today.

### Illawarra

Bathymetric and sedimentological studies of Lake Illawarra provided the basis for description of a typical barrier estuary (Roy and Peat 1975; Young 1976; Jones et al. 1976). The studies contributed to the model of estuarine evolution shown in Fig. 1 (Roy 1984). Further investigations of the stratigraphy and chronology, comprising extensive coring and radiocarbon and amino-acid racemisation dating, have provided more detail on its Holocene evolution (Sloss et al. 2005). Human impacts were already apparent in the 1970s and a clearer assessment of their extent can now be seen from further sedimentary investigations, as well as the impact of direct engineering interventions in recent decades.

The lake serves as a trap for sediment from landward and for sand from seaward. There are three distinct depositional environments in the lake. The central basin is muddy (less than 10% sand) representing a trap for the finer fraction derived from the catchment. The western margin comprises lithic sands, primarily composed of quartz but with other minerals, sourced from the catchment or eroded from the lake shore by wave action. The eastern margin contains extensive well-rounded quartz sand, termed marine sand by Roy (2006), reworked through the inlet by tidal processes onto a flood-tide delta and moved along the backbarrier by wind-wave-driven currents (Roy and Peat 1975).

## Mid Holocene

Based on an average thickness of Holocene sediments in the lake of 5–6 m, a general overall accretion rate of 0.8 mm/yr was inferred by Young (1976). The Holocene evolution of the lake has been divided into 5 stages by Sloss et al. (2005): Pleistocene lowstand; marine transgressive stage (7,600-5,000 years ago); back-barrier lagoon (5,000–3,200 years ago); barrier growth and inlet migration (3,200-2,500 years ago); and restricted inlet and bayhead-delta growth (since 2,500 years ago). The stratigraphic and geochronological studies by Sloss et al. (2005) corroborate that the natural rate of sedimentation in the lake (Fig. 4), prior to European settlement, was of the order of 1 mm/yr or less; however, there is considerable evidence for more rapid sedimentation in the past two centuries.

## Contemporary morphodynamics

An acceleration in the rate of sediment delivery to the lake was inferred by Young (1976), on the basis of the increased area of the Macquarie Rivulet fluvial delta, the extent of which was recorded in historical parish maps of 1834 and subsequent aerial photography. This delta has continued to build into the lake (Hopley et al. 2012), in contrast to the mouth of Mullet Creek which has shown little change. Human activities in the catchment have exacerbated natural erosion, commencing with logging of cedar in the 19th century, then agricultural expansion for a range of crops and dairy farming, and with a substantial spread of urban development since the 1960s.

Rates of accretion following European settlement have been determined using $^{210}$lead and $^{137}$caesium dating, and identification in cores of fly-ash from nearby industrial operations, indicating that up to 40–60 cm of sediment has accumulated in some parts of the lake since 1896 (Jones 1994; Chenhall et al. 1995). In the central lake, mud accretion since European settlement has been occurring at rates of up to 4.5 mm/yr for the past 50 years, whereas vertical accretion of the sandier sediments in the Macquarie Rivulet fluvial delta can occur at rates of 16 to 31 mm/yr (Sloss et al. 2004, 2011).

There have been several attempts to quantify sediment delivery from the catchment. Modelling by CSIRO, using the SedNet model (Prosser et al. 2001), indicated pre-European delivery to the lake to have been 1,600 t/yr, and post-European delivery to average 3,400 t/yr. Using estimates of soil loss by sheet erosion under changing land use within

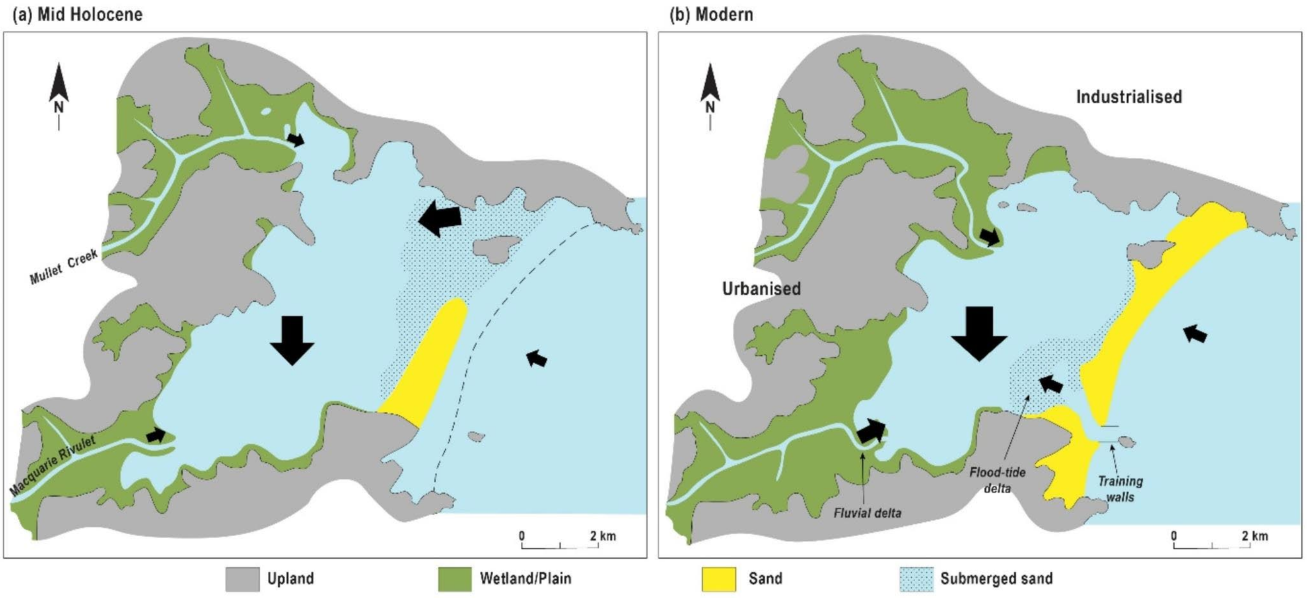

**Fig. 4** Geomorphology of Lake Illawarra barrier estuary, (a) Mid Holocene (~5,000 years ago) and (b) Modern (based on reconstructions by Sloss et al. 2005). The principal components of the sediment budget are shown by arrows

the catchment, three phases have been identified; pre-1817 when the rate of delivery from the largely forested catchment is estimated to have been 23,500 t/yr; 1817–1899, a major land clearing period, during which delivery is estimated to have been 62,194 t/yr; and 1900–1993, a period of urbanisation and industrialisation, in which it is considered to have been 35,334 t/yr (Yassini et al. 1994, Table 9.2, p.97).

Prior to engineering works at the entrance, Warilla Beach was intermittently connected to Windang Island by a tombolo. Sand from Warilla Beach could be transported into the lake's entrance, but its return was prevented by re-formation of the tombolo; a trapdoor effect which exacerbated erosion problems on Warilla Beach (Jones et al. 1976). A training wall was constructed in 2001 that connected the southern side of the entrance channel to Windang Island, effectively changing Warilla Beach into a closed compartment (as opposed to an intermittently leaky one). Warilla Beach was nourished with sand during these works, the consequences of which are discussed below. Training walls have ended that exchange, but they have also enhanced scour in the tidal inlet, altered tidal prisms in the lake, and accelerated sand deposition on the flood-tide delta (Young et al. 2014).

## Shoalhaven

The Shoalhaven River has almost completely infilled its estuary and transitioned to a wave-dominated delta (Carvalho and Woodroffe 2020); it is called a mature riverine estuary by Roy et al. (2001). Development of the beach-ridge plain behind Seven Mile Beach was shown to be related to the Shoalhaven River by Wright (1970), who described the wave processes that accounted for longshore variation and the role of sediment supply from the river, which he considered the principal source of sand from which the ridges had been built. Radiocarbon dating of shell material from several transects across the strandplain indicated that the approximately 40 ridges had prograded from ~6,500 to 1,000 years BP (Thom et al. 1981). A more detailed chronology is now available for both the estuary (Umitsu et al. 2001) and the prograded barrier (Carvalho et al. 2019).

### Mid Holocene

Drilling and dating of sediments beneath the plains flanking the Shoalhaven River (and its tributary Broughton Creek) east of Nowra have enabled reconstruction of the Holocene infill of the barrier estuary that formed at the mouth of the Shoalhaven River (Woodroffe et al. 2000;

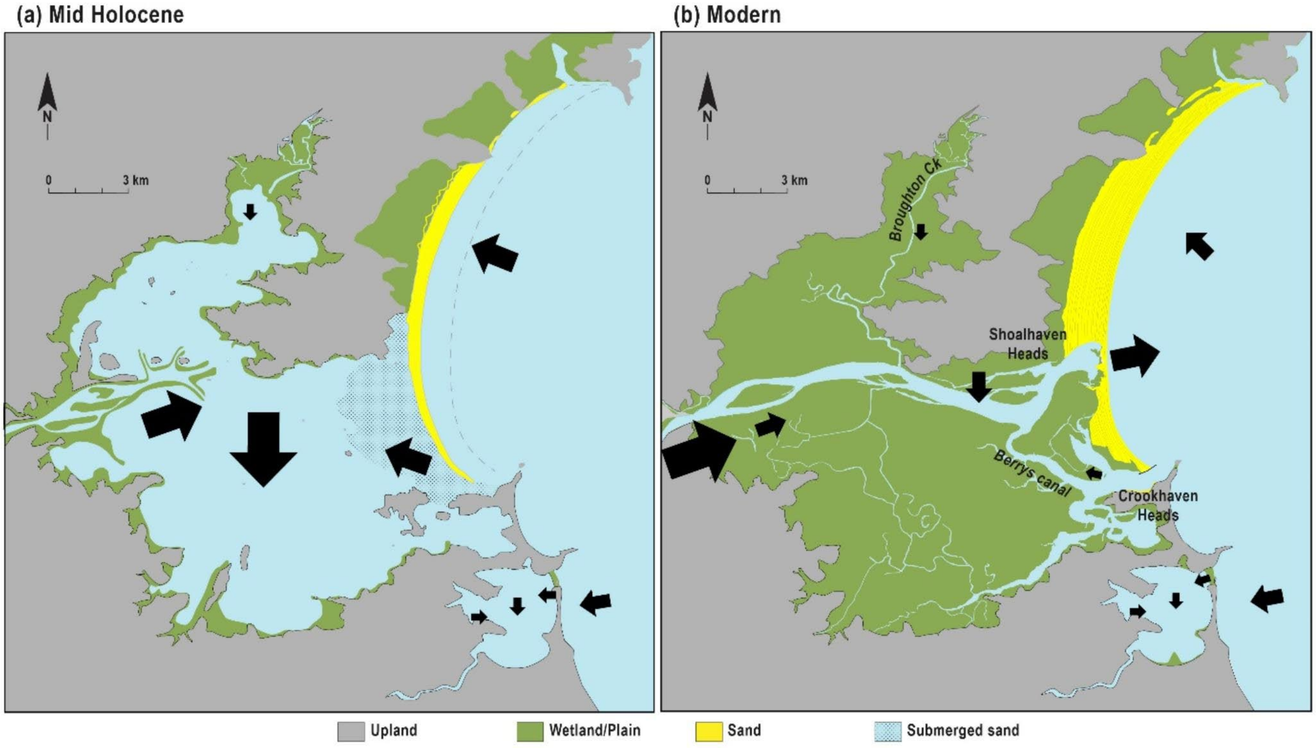

**Fig. 5** Geomorphology of the mouth of the Shoalhaven River, (a) Mid Holocene, and (b) Modern, showing the existence of a barrier estuary ~5,000 years ago and its transformation to a delta today (after Carvalho and Woodroffe 2020). The principal components of the sediment budget are shown by arrows (Note: Sediment delivery from the catchment has increased, but most of this is trapped by Tallowa Dam that is upstream of Nowra)

Umitsu et al. 2001). The pattern of infill corroborates the broad conceptual model proposed by Roy (1984; 1994). Inundation of the prior valley occurred in the final stages of the postglacial transgression with deposition of shell-rich sands, followed by vertical accretion of estuarine muds in the central mud basin (Fig. 5). In this early stage of infill the Shoalhaven barrier estuary would have resembled the landscape presently observable at Lake Illawarra. However, the larger catchment and the greater supply of fluvial sediment from the Shoalhaven River resulted in infill of most of these estuarine environments by ~ 3,000 years ago. Sedimentation rates of 3–4 mm/yr appear typical of the floor of the estuary, with higher rates associated with the fluvial delta that prograded into the estuary (Umitsu et al. 2001). Paleochannels evident from LiDAR, indicate that the Shoalhaven River meandered across the infilled plains, and formerly exited at Crookhaven Heads (Carvalho and Woodroffe 2020).

Morphostratigraphy and optically-stimulated luminescence (OSL) dating has indicated that the turnaround from transgression to regression, recorded at the landward margin of the Seven Mile Beach strandplain as well as at Moruya, occurred around 8,000–7,000 years ago (McBride et al. 2020). Although some evidence has been postulated for delivery of fluvial sands to the coast in Mid Holocene (Young et al. 1996), the contribution of lithic and angular sand sourced from the catchment becomes apparent in the Seven Mile beach-ridge sequence from around 3,000 years ago. Dating of ridge deposition by OSL, has refined the earlier radiocarbon chronology and provides a clearer indication of the progradational history sequestered in the 15 km$^2$ of strandplain (Carvalho et al. 2019). The landward-most ridge retains a morphology (with distinctive flame structures) indicating overwash at the culmination of the transgressive phase around 8,000 years ago, after which successive ridges were deposited in the ensuing regressive phase, with progradation at an average rate of 0.17 m/yr (McBride et al. 2020). The landward sequence of ridges built seaward at an average rate of ~ 0.12 m/yr until around 2,400 years ago, and the more seaward ridges prograded at an average rate of ~ 0.22 m/yr, augmented by the addition of fluvial sand (Carvalho et al. 2019). For the past 600 years a rate of 0.32 m/yr has been inferred, although this is complicated both by the shorter time over which the average is calculated and formation of a substantially higher foredune than typical of older ridges.

### Contemporary morphodynamics

The large catchment, of heterogeneous geology and land-use, supplied sediment that was deposited more rapidly in this barrier estuary, infilling much of it by 3,000 years ago. Increased sediment supply from the catchment is likely in the past 200 years, but most is now trapped in Lake Yurrunga since the completion of Tallowa Dam in 1972. The CSIRO SedNet approach estimated pre-European fine sediment delivery rates of 9,000 t/yr, and post-European rates of 137,200 t/yr (Prosser et al. 2001). Based on comparison of bathymetric surveys of the lake 11 years apart, an average of 720,750 t/yr appears to have been brought into the lake (Carvalho 2018). Assuming a trapping efficiency of 88%, and adding an estimated supply from an unmodified creek downstream of the dam, Carvalho has calculated that the Shoalhaven River delivers 86,000 m$^3$/yr (133,300 t/yr) on average to its estuarine channel (Carvalho 2018). Construction of Tallowa Dam has had further consequences, reducing the severity of major floods.

Although little accommodation space remains in the estuarine channel of the Shoalhaven River, comparison of bathymetric surveys taken in 1981 and 2006 indicates net deposition of 400,000 m$^3$ in that 25-year period. The lower Shoalhaven River is still adjusting its hydrodynamics and morphology to diversion through Berrys Canal in 1822, despite evidence that the river took this route in the past. There is extensive riverbank erosion, particularly along Berrys Canal, and the estuarine channel continues to be a sink for a proportion of the incoming sediment. This is despite extraction of 620,000 m$^3$ of sand aggregate on the southern bank of Pig Island in the 25-year period over which terrain modelling provides insights into morphological change (Carvalho 2018; Carvalho and Woodroffe 2021).

Bathymetric surveys of the shoreface adjacent to Shoalhaven Heads record a crescentic bar that was present in 1981, but which had been largely re-distributed along the nearshore by the subsequent 2006 survey (Carvalho 2018). Shoalhaven Heads remains closed by vigorous swell action most of the time. Sediment delivery occurs episodically during major flood events when the Heads are breached.

## Moruya

Fluvial sediments from the Moryua River have been deposited within alluvial plains around the town of Moruya, infilling a Holocene estuarine basin (Oliver et al. 2020), but only minor amounts of angular feldspar-rich sands reach the adjacent coast (Hall 1981). Fine sediment delivery is estimated by the CSIRO SedNet approach to have been 600 t/yr prior to European settlement, and 24,400 t/yr since.

The beach-ridge sequence forming the prograded barrier (strandplain) behind Bengello Beach, north of Moruya, has been the site of several studies. Drilling and radiocarbon dating was undertaken in the 1970s, and the Holocene evolution of the area determined by Thom et al. (1981). Investigations of transects in the north, centre and south of the plain revealed basal estuarine clay, overlain by transgressive sand, which in turn transitions into a regressive sequence of beach ridges, topped by foredune sands. Complementing this millennial-scale study, sub-annual profiles have been surveyed across the beach and foredune at four sites commencing in 1972, providing one of the longest such records anywhere in the world from which to understand depositional and erosional processes (Thom and Hall 1991).

## Mid Holocene

Holocene reconstruction has been undertaken for several of the beach ridge sequences that comprise prograded barriers near Moruya (Oliver et al. 2020), using high-resolution morphology based on airborne topographic and marine bathymetric LiDAR data, together with further dating by OSL. The beaches to the north contain substantial carbonate content, derived from the skeletal remains of molluscs and encrusting organisms on the intertidal and submerged rocky outcrops. Their development is not considered further here, except to note that progradation has built a salient that later became a tombolo connected to Broulee Island, and this has divided a formerly longer Bengello Beach into two compartments with largely independent sediment budgets.

OSL dating (which provides an age for time of burial of quartz sand grains, as opposed to time of death of contributing organisms derived from radiocarbon analyses of shell hash) implies progradation of beach ridges at a relatively constant rate of ~ 0.27 m/yr for the past 7,000 years, in contrast to earlier radiocarbon chronology for the central transect behind Bengello Beach, from which decelerating progradation was inferred (Oliver et al. 2015).

OSL dating of beach ridges at Pedro Beach indicates progradation from ~ 6000 years at an average rate of 1.2 m/yr, slowing after ~ 5200 years to ~ 0.38 m/yr, and ceasing ~ 4000 years ago, with subsequent construction of a tall foredune that is less than 200 years old (see Oliver et al. 2019 for details). This has been interpreted to indicate that sand supplied to Pedro Beach from offshore in the past 4,000 years has bypassed the headland to the north and contributed to the adjacent tertiary compartment, Moruya Heads Beach. At that beach, the landward most ridge has been dated to around 4,500 years ago, with progradation of 0.19 m/yr until ~ 3,000 years ago, then slowing to 0.03 m/yr (Oliver et al. 2020).

## Contemporary morphodynamics

The ongoing beach surveys at Bengello Beach began in 1972, just prior to major storms in 1974 which caused significant erosion along much of the NSW coast (Thom 1974; Bryant and Kidd 1975). Although the return period of such events is still debated, the consequences have been considered an indication of the extent of erosion that might be anticipated in a 'one-in-a hundred-year' event (Tamura et al. 2019). The beach retreated by as much as 50–60 m, with removal of about 95 $m^3$ of sand (see Fig. 7). Storm erosion removed sand from the beach, depositing it in the nearshore; but it took almost a decade for the beach to return to its pre-storm position (Thom and Hall 1991; McLean and Shen 2006). Cut and fill is a feature of frequent storms along the coast of southeastern Australia, with erosion of beach berm and deposition in the nearshore; smaller storms are usually followed by more rapid recovery over ensuing months.

The ongoing surveys at Bengello indicate fluctuations that can be experienced on exposed beaches in southern NSW, and while there is more detailed and increasingly sophisticated monitoring at Narrabeen-Collaroy Beach in Sydney, commencing in 1976, the record from that site does not incorporate the large volume of sand eroded during the 1974 storms. Supplementing the decades-long surveys of Bengello Beach, surveys along Moruya Heads and Pedro Beaches record that these oscillate in planform, showing beach rotation that is synchronous with that observed on Narrabeen-Collaroy Beach, with shoreline displacement of

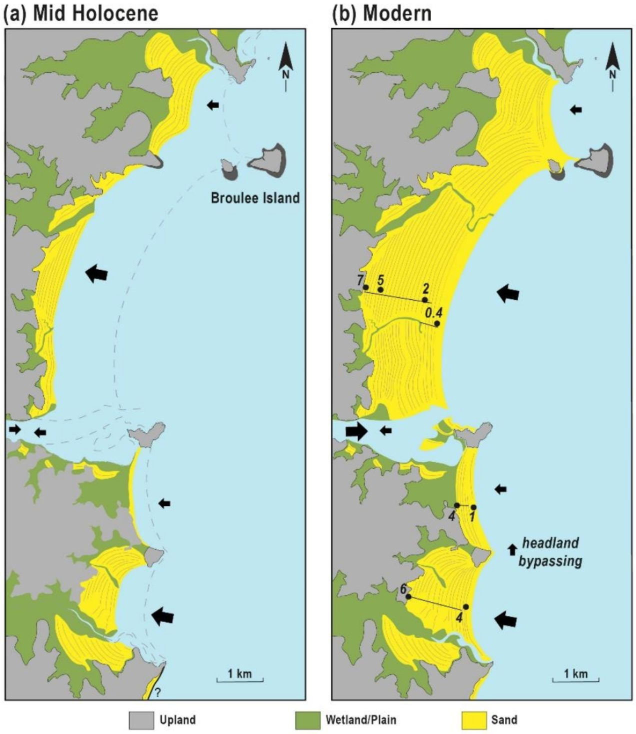

**Fig. 6** Geomorphology of the coast near Moruya, (a) Mid Holocene (~ 5,000 years ago), and (b) Modern. Transects along which ridges have been dated by OSL are shown, with OSL ages (dots) on sand samples at the ends of the transect (in thousands of years). The principal components of the sediment budget are shown by arrows (after Oliver et al. 2020). Offshore reefs, not shown, interrupt longshore sediment transport (see shaded area on Fig. 7 for details)

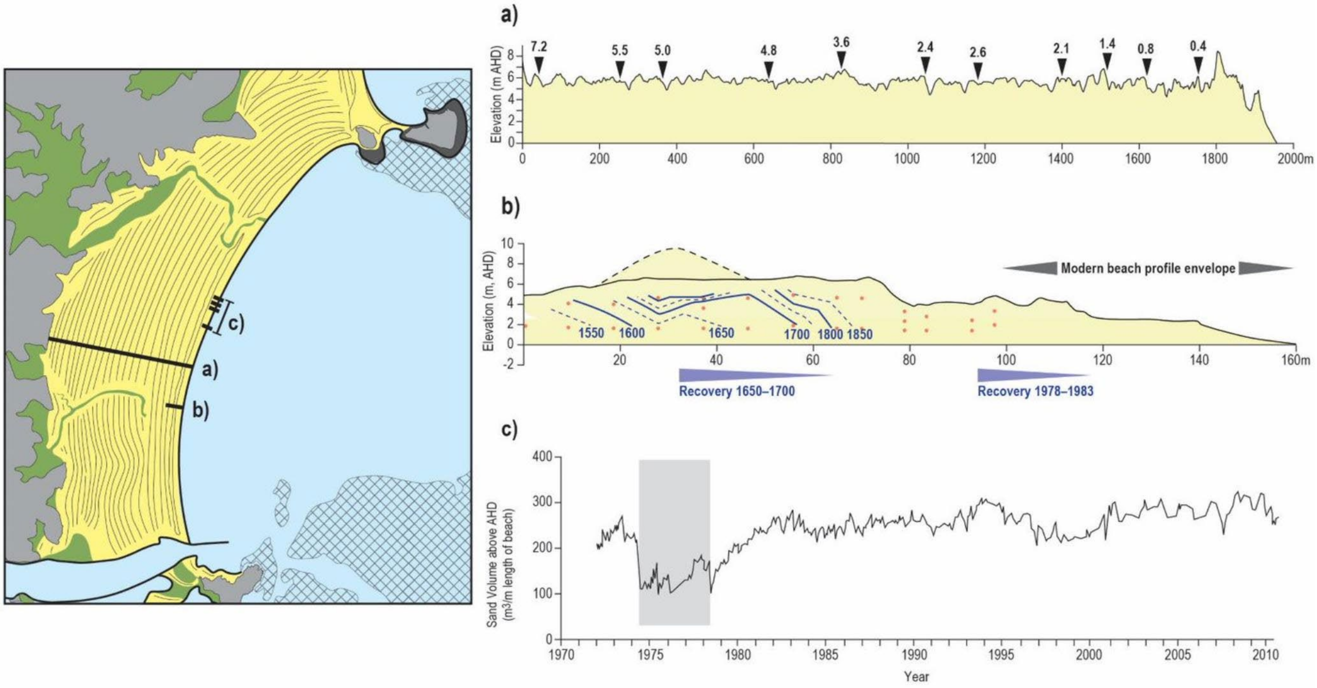

**Fig. 7** Bengello Beach, showing the results of studies at millennial, centennial and decadal time scales: (a) morphological profile across the beach ridges along which OSL ages record progradation (after Oliver et al. 2015), (b) cross-section of seawardmost ridges and OSL chronology with evidence of recurrent recovery following storm erosion (after Tamura et al. 2019), and (c) volume of sand (above MSL) in 4 profiles of the beach and foredune from regular re-surveys over recent decades (after McLean et al. 2010)

tens of metres in response to El Niño-Southern Oscillation variation (Short et al. 2014).

## Discussion

The three selected compartments represent contrasting environments with substantial differences between them in terms of sediment budget, and a history that reveals changes in sediment transport in the past. This discussion builds on the review of past geomorphology by considering how this provides the context for understanding contemporary morphodynamics, including engineering structures at the entrances and sediment delivery to specific habitats. It serves to illustrate how these studies across timescales can provide otherwise unavailable insights into long-term patterns of sediment movement. This, in turn, may enable better adaptation in future, both to ensure that engineered solutions are not maladaptive, and to make planning decisions in the face of changes in sea level and other environmental factors.

Lake Illawarra, an immature barrier estuary surrounded by urbanisation, remains a sink for sediment, although with significantly more rapid rates of vertical accretion than observed in past millennia. The Shoalhaven River has infilled the plains that flank it, and now supplies fluvial sediment to the nearshore and to the prograded barrier to its north; its sediment budget has been altered by several significant human interventions. Moruya contains several prograded barriers, but receives little fluvial sediment, and is the least affected by human activities. It provides a setting in which adjacent tertiary compartments have accreted at different rates, changing their alongshore connectivity.

Assessments of sources of sediment, rates of supply, and transport pathways are fundamental to determining a sediment budget, and necessary to better constrain future shoreline response, whether the contemporary patterns of sediment movement continue, and especially if they alter in response to anticipated changes in sea level and wave climate. It is apparent from the comparison of neighbouring compartments along this embayed shoreline that coasts exposed to a similar regional sea-level history, wave climate and storm incidence, can each behave differently. However, it remains challenging to determine rates of sand movement on the shoreface under present conditions and in future; the shoreface may act as a source or sink, depending on its relationship with the beach, local wave climate, and the sea-level rise scenario adopted (Goodwin et al. 2020).

## Periodicity across timescales

Geomorphological reconstructions of landform evolution in mid Holocene provide cumulative depositional rates, but it is not clear to what extent these long-term millennial patterns of sedimentation might still be occurring at timescales intermediate between millennial and historical. Moruya represents one of the most effective settings in which to compare and contrast sedimentary processes over the range of millennial, century, decadal and annual timescales, and understand the role played by events of differing magnitude and frequency (Thom and Bowman 1980). At Bengello Beach, 60–80 ridges have accumulated in the ~7,000 years since sea level reached close to its present elevation.

Periodicity in landform development is clearly apparent; the strandplain comprises a sequence of beach ridges forming a crest-swale topography, with episodic ridge creation approximately every 110 years (Fig. 7). Foredune re-establishment has been observed following a cluster of successive 'east coast low' storms in 1974 and a further major storm in 1978 (McLean and Shen 2006). Recovery of shoreline position and beach volume took almost a decade (Thom and Hall 1991); minor erosional episodes have occurred since then, (McLean et al. 2010). However, the triggers for successive ridge generation remain only partially understood, as monitoring has only been maintained for approximately half the average lifetime of a ridge.

Cut and fill episodes like those seen in the observations must have occurred during gradual accretion of successive ridges, but the depositional archive has preserved a sedimentary record only of the cumulative progradation. In a recent application of OSL dating, Tamura et al. (2019) reconstructed the depositional history over the past 400–500 years near sites that have been surveyed for the past few decades (Fig. 7). Their study provides a century-scale perspective, identifying one or more episodes of cut and recovery similar to the major storm erosion during the 1974-78 period. The volumetric addition of 1.5-2 $m^3$/m/yr from the several decades of surveys compares very well to the net accretion (above MSL) over the Holocene that is also ~2 $m^3$/m/yr. These equate to ~0.28 m/yr from the profiles compared to ~0.27 m/yr inferred from OSL dating of past shorelines (Tamura et al. 2019), although the progradation trend is obscured because of disruption from periodic storms.

In contrast to this relatively constant ongoing pattern of sedimentation with its irregular perturbations (also observed further south on the NSW coast by Oliver and Tamura 2021), system behaviour can change over time as a result of external factors. Despite the apparent constancy of overall buildout, accommodation space has changed progressively, and Bengello Beach, previously confined by small headlands, has broadened, connecting in mid Holocene with the beach in the embayment to its north. Establishment in the past 2,000 years of a tombolo, linked to Broulee Island, has again partitioned them into two compartments.

The two tertiary compartments to the south contain strandplains that superficially resemble that at Bengello Beach, but with contrasting accommodation space. Pedro Beach is a highly crescentic embayment and the OSL chronology indicates rapid infill with sand from offshore by around 4,000 years ago (Congo Creek is only a minor contributor). OSL dating of ridges behind Moruya Heads Beach, where there seems the least accommodation space, indicates that it commenced ridge building around the time Pedro was full, and received its sediment via alongshore transport from Pedro Beach to the south (Oliver et al. 2019, 2020).

## Offshore sediment supply and contemporary shoreline budget

As sea level rose during the postglacial marine transgression, it reworked landwards sand that had accumulated on the shelf (Roy et al. 1994), building barriers that occur along the NSW coast (Fig. 2). However, it is not easy to determine if there is still an ongoing supply of sand from offshore sources. Whether or not particular compartments are experiencing a positive sediment budget is an important management concern. In each of the Illawarra, Shoalhaven and Moruya secondary compartments it seems likely that some beaches (tertiary compartments) are being supplemented by this offshore source of sand, as has been inferred for a similar strandplain in central NSW (Kinsela & Daley, 2016).

There are two datasets that provide historical perspective on shoreline changes for much of the NSW coastline. Beach morphology has been determined photogrammetrically along profiles across many NSW beaches by the state government; these profiles have recently been made available for analysis (Harrison et al. 2017). The record is sporadic as vertical aerial photographs of varying quality were captured many years apart. The second dataset is the Digital Earth Australia (DEA) coastlines data (Bishop-Taylor et al. 2021), based on 30 years of satellite imagery (primarily Landsat) processed to generate an averaged 'annual' shoreline position using a subset of imagery acquired when the overpass occurred close to the time of mean tide level. Further analysis of these datasets and more sophisticated data, such as LiDAR, offer considerable opportunities for higher resolution quantification of future shoreline changes, beyond the scope of this review. However, a brief comparison is made of trends from these approaches with the longer-term trends described above.

Aerial photographs have been analysed to investigate patterns of change in the Illawarra compartment. A volumetric increase of 123 $m^3$/m averaged along Perkins-Windang

Beach, corresponding to an average rate of 2.32 $m^3$/m/yr has been estimated from the photogrammetry for the 53 years from 1961 to 2014 (Doyle 2019). Kinsela et al. (2020) compared shoreline position for beaches between 1980 and 2018, using the photogrammetric database. They found evidence of beach rotation with progradation of Perkins Beach to the north, and retreat of Windang Beach to the south. Assessment of shoreline position using the DEA reconstructions averaged for the period 1988 to 2018 indicates slight shoreline progradation (averaged annual progradation along the entire beach of 0.22 ± 0.19 m). The suggestion of slight progradation, despite sand being transported into the lake through the entrance, further supports an ongoing delivery of sand from the shoreface. Warilla Beach serves to illustrate that the DEA approach does pick up major trends in beach position. Approximately 100,000 $m^3$ of sand was pumped from the entrance and added to Warilla Beach as nourishment during the entrance engineering works in 2001 (Fig. 8a), with a further 200,000 $m^3$ added in 2007, when a second training wall was constructed on the northern side of the channel (Doyle et al. 2019). The respective additions are apparent in the DEA satellite record of annual shorelines.

Comparing shoreline position along Seven Mile Beach using the vegetation line on aerial photographs in 1972 and 2013 when Lidar became available, Carvalho and Woodroffe (2021) infer a volumetric addition over those 41 years. It seems clear that the principal source of sand during mid Holocene has been well-rounded quartz sand derived from a seaward source that has been supplemented in recent millennia by sand that the Shoalhaven River delivers episodically to the shoreface when major floods open the former river mouth at Shoalhaven Heads. Seismic results have shown coarse to very fine sand offshore that is thicker adjacent to Seven Mile Beach compared with further south, where there are two tertiary compartments bounded by extensive rocky outcrops (Roy and Ferland 1987; Carvalho 2018). Further evidence for ongoing progradation comes from the DEA coastlines dataset which implies that Seven Mile Beach is continuing to prograde, with an annual progradation rate over 30 years of 0.91 ± 0.19 m/yr. By contrast, Culburra Beach, the tertiary compartment to the south, receives negligible fluvially-derived sand and comparison of photogrammetric data indicates that it has lost sand in recent decades (Doyle 2019).

**Fig. 8** (a) The entrance to Lake Illawarra in 2001 at the commencement of construction of a training wall on its southern margin. At this time sand from Warilla Beach could be moved into the lake entrance. This has since been prevented by the training wall, and Warilla Beach has been nourished with sand from the channel. (b) The mouth of the Shoalhaven River with Crookhaven Heads in the foreground. Berrys Canal is continuing to widen

The principal source of the sand that contributed to former beach ridges at Bengello Beach also appears to be from offshore, with negligible contemporary fluvial input. Limited photogrammetric data from Bengello Beach, since the 1980s, indicates build out, and the DEA analysis indicates progradation (0.19 ± 0.21 m/yr averaged for the entire beach, but with considerable year-to-year variability. Neither of these datasets provides the level of detail available from the repeat surveys multiple times per year since 1972 (Fig. 7). The beach ridges behind Moruya Heads Beach and Pedro Beach are also considered to be sourced from sands that have accumulated on the inner continental shelf over the past several million years, but extensive rocky outcrops imply more localised sediment delivery (Oliver et al. 2020).

The component of the sediment budget in the nearshore remains the most difficult to assess. The shoreface could be either a source or a sink for sand (Goodwin et al. 2020). Extending the shoreface translation model (Cowell et al. 1995, 2006), Kinsela & Daley, (2016, 2020) have proposed that shoreface morphology provides a guide to likely interconnectivity of beach and shoreface, when compared with the anticipated equilibrium morphology (Ortiz and Ashton 2016). They designate the shoreface as 'underfit' if it is below the concave profile that would represent equilibrium and therefore has accommodation space within which sand lost from the beach can be deposited. They consider it 'overfit' where there is sand in excess of that morphology. This approach has been demonstrated using recently acquired high-resolution bathymetry (state-wide LiDAR and multibeam mapping data) and sedimentary mapping of the seabed for the Illawarra compartment (Kinsela et al. 2020).

## Anthropogenic impacts

Evidence of human modifications of the sediment budget differs between compartments. Although there is anecdotal evidence that the local aboriginal inhabitants, the Wodi Wodi people of the Dharawal nation, may have attempted to cut an opening at the entrance, scratching with sticks, when Lake Illawarra was closed but water levels were high (Davis 2005), direct impacts occurred following European settlement in the late 18th century. Clearing of vegetation in the 19th century, initially through extraction of selected timber, but subsequently with expanding agriculture and urbanisation have augmented sediment supply from catchments. Stratigraphic and dating studies in Lake Illawarra, described above, have shown that sediment accretion has accelerated in the central basin, more than doubling Holocene rates. Increased sedimentation is locally apparent in fluvial and flood-tide deltas.

The permanent opening of Lake Illawarra has resulted in significant geomorphological, hydrodynamic and ecological changes. The hydraulic efficiency of the inlet has increased with erosion of the northern shoreline and deposition of additional sand on the flood-tide delta; the tidal prism of the lake has increased; it is more saline and water levels around its margin have changed with implications for the distribution of wetland vegetation such as mangroves. These issues have been subject to a major review and are addressed as part of the Lake Illawarra Coastal Management Program (2020–2030), see Rollason and Donaldson (2020).

The Shoalhaven compartment has experienced several modifications that have affected sediment pathways. Although the transition from an estuarine trap during mid Holocene to a delta that is a net exporter of sand has been a natural progression, rates of sediment transfer have been substantially modified by human activities. There is some archaeological evidence for use of coastal resources by indigenous Aboriginal inhabitants; shell remains, including oysters, from rock shelters beside the Shoalhaven River near Nowra, indicate that people have been foraging here for at least 2,000 years (Lampert and Steele 1993). However, it seems unlikely that their activities had discernible consequences for coastal landforms. Further modification has occurred in the past 200 years with drainage of wetlands, modifications to creeks, and installation of floodgates to ameliorate acid sulphate soil conditions.

Dam construction has reduced the incidence of floods. Lake Yurrunga traps much of the increased sediment contribution from the catchment. It is less clear how anthropogenic activities have modified the transfer of sediment through the estuarine channels of the lower Shoalhaven that has little accommodation space left. Major floods breach Shoalhaven Heads and deliver fluvial sand episodically to the nearshore, which augments ongoing progradation of Seven Mile Beach (despite conspicuous erosion of the beachface and dune toe by waves). The lower Shoalhaven is still undergoing morphological changes following the excavation of Berrys Canal. Continuing riverbank erosion indicates that the channel is not yet in equilibrium with tidally and fluvially driven flows (Fig. 8b). Although this has been an unnatural change for the system, there is geomorphological evidence that the river has previously changed its course naturally, including having exited through a mouth at Crookhaven Heads.

Sediment budgets around Moruya appear relatively unaltered by human activity, despite inferred increased sediment delivery by the Moruya River as a result of extensive clearing and alluvial gold extraction in the catchment. Engineering interventions, such as installation of hard protection to the river banks in the tidal reach and training walls, will have altered the pattern and rate of sediment transfer.

There has been less attention as to how human activities have affected individual beach and dune systems. Unrestricted recreational activity on dunes had led to sand drift in the past and many foredune systems along the more populated parts of the NSW coast are managed with access limited to defined walkways, and re-vegetation of some impacted dunes. There is little documentation of whether these managed foreshores behave differently from those where there has been no intervention. It is noticeable that the most recent foredune or dune ridge in each of the studied prograded barriers is taller and contains a larger volume of sand than the relict dune sand that tops former beach ridges (see, for example, Fig. 7a). There has been some suggestion that this apparent change may reflect anthropogenic related land-use change (Oliver et al. 2020). While this is still unclear, the discrepancy between the morphodynamics of systems in the past and how they may be behaving now needs to be taken into account when inferring modern rates of sedimentary processes from Holocene geomorphological studies.

## Boundary conditions

For the purposes of this study, some boundary conditions have been considered not to have changed, and it is important to specify these. First, the overall climate of this region is assumed to have remained unchanged. Changes to the global climate over the past century or more have been documented in successive assessments by the Intergovernmental Panel on Climate Change (IPCC), and their projections of future changes in climate will have consequences for coastal environments, but these are beyond the scope of this study.

Second, sea level is regarded as having been relatively stable throughout the past 6,000–7,000 years. Sea level has been shown to have exerted a major constraint on coastal landforms and ecosystems. The rise of sea level since the last ice age resulted in translation of shorelines across the inner continental shelf. The transition from transgression to regression marked commencement of many of the key geomorphological processes, in particular formation of sandy barriers as sea level stabilised, occluding estuaries that then started infilling, each progressing through an evolutionary sequence at its own pace. Simultaneously, strandplains commenced progradation where there was an adequate supply of sand. Although there is some evidence for the sea having been slightly above its present level (~ 1 m higher) perhaps until as recently as 2,000 years ago (Sloss et al. 2007), these past variations in sea level are not regarded as having an as-yet detectable effect on the geomorphological evolution of the coastal compartments studied.

However, projected sea-level rise that is anticipated as a consequence of climate change is a pressing issue for which coastal managers need to plan. Sea-level rise has been observed since tidal records began at Fort Denison in Sydney, and a detectable pattern of sea-level rise is shown by the SeaFrame tide gauge at Port Kembla since 1993, coincidentally at a rate very similar to the global mean sea-level rise recorded by satellite altimetry over the same period of ~3.4 mm/yr. If that rise has caused a small retreat in mean shoreline position, it remains noise within general shoreline fluctuations, particularly as several of these beaches experience beach rotational shifts of tens of metres (Short et al. 2014). By contrast, data on shoreline position for the strandplains that have had a history of progradation over millennia appears to indicate ongoing build out. This also seems the case for the Windang transgressive dune barrier that appears to be nourished by fresh sand from offshore. Some of this sand is sequestered in the dune system behind the beach, and some moved into the tidal channel (although this may have been interrupted by the recently constructed training walls), and ultimately onto the flood-tide delta in Lake Illawarra.

The third set of boundary conditions that are known to vary, but that have been treated as stationary in this synthesis are the oceanographic controls, particularly the wave conditions. Beaches are especially responsive to wave forcing; beach state is a function of antecedent morphology, and recent and ambient wave climate. Erosion of beaches happens rapidly during storm events but subsequent recovery occurs much more slowly, often over weeks, or months, or in the case of particularly extreme storms, such as those of 1974 and 1978, over years and even decades (see Fig. 7). Ongoing monitoring of Narrabeen-Collaroy Beach reveals rotation of shoreline position in response to dominant wind directions that are influenced by the El Niño-Southern Oscillation phenomenon (Ranasinghe et al. 2004). Still longer-term adjustments in response to prevailing atmospheric conditions have been shown to be important at millennial timescales (Goodwin et al. 2006).

## Overview and conclusion

Three separate secondary compartments on the south coast of NSW have been described. Each of these has been the subject of geomorphological investigations since the 1970s, focused at both millennial and observational timescales. This makes it possible to compare past rates of process operation with contemporary rates. It is important to recognise that sedimentary records are an incomplete archive and that there are likely to have been many perturbations at intermediate timescales. However, understanding past behaviour at decadal to century scale can guide management of entrances to waterways, and enable decision-makers to plan for the future, adopting appropriate conservation and adaptation strategies in the face of anticipated climate change.

Estuarine systems can undergo abrupt changes in sediment pathways when they pass particular thresholds, as is apparent from the likelihood that both the Shoalhaven and Lake Illawarra have had alternative entrances in the past. The Shoalhaven transitioned from an estuary to a delta around 3,000 years ago when it had largely infilled its embayment. Similar thresholds appear to have been reached in other systems; for example, Pedro Beach exceeded its accommodation space around 4,000 years ago, with bypassing of sand to Moruya Heads Beach, which then began prograding.

Geomorphological studies since the 1970s, initially using radiocarbon dating but extended with more recent dating techniques, provide insights into sediment pathways, enabling estimates of rates of vertical accretion and shoreline change. These preliminary two-dimensional assessments can form a basis for subsequent volumetric estimates of process operation, including whether estuarine entrances are importing or exporting sand. The availability and supply of fine-grained sediment plays an important role in terms of the extent of estuarine habitats, and efforts to conserve ecosystems, such as wetlands. The provenance of sand and its transport is also relevant to the dynamics of landforms, such as flood-tide deltas, and affects the viability of nature-based solutions on the coast.

Although geomorphological studies can indicate general patterns of sediment transport, there remain several complicating factors. First, many transfers of sediment are bidirectional. This is certainly the case with tidal exchange, and, over a longer timescale, with cut and recovery processes in beach and dune morphodynamics. Second, many of the transport processes are episodic with disproportionately large effects associated with extreme and rare events. Finally, the boundary conditions under which the system has operated may not remain constant; fluctuations around an oscillating set of conditions may gradually transition in response to altered environmental forcing. This is particularly the case in terms of sea-level rise, about which managers and planners need to be especially mindful.

Sandy shoreline response to the increase in sea level over past decades remains undetectable, and as yet within the morphodynamic variability demonstrated for each of these coastal sediment compartments. For several of the tertiary compartments an ongoing supply of sand from the shoreface appears likely, although at barely measureable rates. Anthropogenic impacts have altered rates of sediment delivery from catchments, modifying what would have been the natural pattern of change. Direct engineering interventions have been considered necessary in some cases, and these have further modified rates of process operation, sometimes with unintended consequences. Sea-level rise will need to be taken into consideration in managing coasts in future, but these contrasting coastal compartments have different sediment budgets and the impacts of sea-level rise on individual beaches are likely to vary from beach to beach.

**Acknowledgements** This study arose from a sediment compartment project supported by the National Climate Change Adaptation Facility. Data presented in this study were partially supported by the Australian Research Council Linkage project LP130101025 and Discovery project DP150101936. RCC was supported by the Brazilian Government *via* the Council for Scientific and Technological Development (CNPq)'s Ph.D scholarship number 202096/2012-2. We thank Tom Doyle and Oxana Repina for analysis of shoreline change rates that are referred to in this paper, and Andy Short and Mike Kinsela for their insights into the behaviour of individual compartments.

**Funding** Open Access funding enabled and organized by CAUL and its Member Institutions

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