# Decadal shoreline erosion and recovery of beaches in modified and natural estuaries

Thomas E. Fellowes[1,2*], Ana Vila-Concejo[1,2], Shari L. Gallop[3,4], Ryan Schosberg[1,2], Vincent de Staercke[5,6], John L. Largier[7,8]

[1]Geocoastal Research Group, School of Geosciences, Faculty of Science, University of Sydney, Sydney, Australia.

[2]Marine Studies Institute, Faculty of Science, University of Sydney, Sydney, Australia

[3]School of Science, University of Waikato, Tauranga, New Zealand

[4]Environmental Research Institute, University of Waikato, Hamilton, New Zealand

[5]Geographic Information Systems Laboratory, École Polytechnique Fédérale de Lausanne, Switzerland

[6]Department of Earth and Environmental Sciences, Macquarie University, Sydney, Australia

[7]Coastal and Marine Sciences Institute, University of California Davis, Bodega Bay, United States of America

[8]Department of Environmental Science and Policy, University of California Davis, Davis, United States of America

*This manuscript has been submitted for publication in GEOMORPHOLOGY. Please note that, despite having undergone peer-review, the manuscript has yet to be formally accepted for publication. Subsequent versions of this manuscript may have slightly different content. If accepted, the final version of the manuscript will be available via the 'peer-reviewed Publication DOI' link on the right-hand side of this webpage. Pease feel free to contact the authors.*

***Corresponding Author:** Thomas E. Fellowes

Email: thomas.fellowes@sydney.edu.au

Postal Address: Geocoastal Research Group, Madsen Building (F09), The University of Sydney, New South Wales, 2006, Australia.

**ABSTRACT**

Sandy beaches in estuaries and bays (BEBs) are common landforms on the coasts of many major cities. They exist under a wide range of settings and their morphology is controlled by their distance from the estuary/bay entrance, exposure to different types of waves (e.g., ocean swells vs locally generated wind waves), proximity to flood-tide delta/shoals, and anthropogenic interventions (e.g., dredging, groynes). Both swell waves propagating into estuaries/bays and locally generated wind waves can erode BEBs. However, more understanding of BEB storm erosion and recovery over decadal timescales is needed, as they typically respond slower than open coast beaches. Here we present decadal shoreline behaviours of nine BEBs from two estuarine systems in SE Australia, using 76 years of aerial imagery (1941–2017). We quantify and compare decadal behaviour between beaches, developing a new typology of BEBs based on shoreline evolution. We identify four decadal behaviours: *prograding*, *quasi-stable*, *retreating* and *relict* – and we assess the influence of flood-tide deltas, river mouths, distance from the entrance, and anthropogenic interventions. Swell-exposed BEBs near the entrance are *quasi-stable* and recover after storms at rates comparable to open coast beaches (<3 years). In contrast, BEBs further from the entrance and those with less swell exposure, have slower recovery timescales (3–15 years) and are controlled by storm return timescales. *Prograding* BEBs are typically far from the entrance, where fluvial, tidal and wind-wave processes dominate. Whether BEBs partially recover between storms (*retreating*) or never recover (*relict*) relates to storm frequency, recovery rates and proximity to sediment sinks (e.g., dredge sites, flood-tide deltas, tidal channels). Further, some BEBs are negatively impacted by anthropogenic interventions with slower recovery and/or prolonged erosion. Findings will help to better understand and manage BEB shorelines in major cities.

**KEYWORDS**

Sheltered beach; low energy beach; storm erosion; beach recovery

## 1. INTRODUCTION

Sandy beaches in estuaries and bays (BEBs) are common landforms worldwide, found in many major coastal cities. Their morphology depends on multiple factors, including sediment supply, geological setting, proximity to flood-tide deltas, swell and local wind wave exposure (Vila-Concejo et al., 2020). In some cases, anthropogenic interventions such as dredging, groynes or revetments also influence BEBs (Lowe and Kennedy, 2016). BEBs are typically considered steep and narrow, and have been traditionally classified as 'low-energy' and dominated by local wind-wave fetch and alongshore sediment transport (Nordstrom and Jackson, 2012). However, ocean swell and infra-gravity waves that propagate into estuaries, as well as tides, currents and boat wakes may also be important for BEB morphodynamics (Jackson, 1995). Although BEBs are typically at least semi-protected from ocean waves, they can still experience erosion events due to storm waves from certain directions that can enter the estuary/bay (Vila-Concejo et al., 2010). When this happens, BEBs can experience significant erosion, proportionate or greater than open coast beaches, with slow or limited post storm recovery (Gallop et al., 2020).

There is a lack of understanding of the mechanisms that control BEB recovery (Nordstrom and Jackson, 2012), and it is clear that BEBs cannot be considered as scaled-down versions of open coast beaches (Vila-Concejo et al., 2020). While it is thought that there may be insufficient wave energy to facilitate full recovery after storm erosion, BEBs would not exist without sufficient wave energy to build them (Nordstrom and Jackson, 2012). Rather, it appears that beaches typically protected from swell recover at slower rates than open coast beaches (Costas et al., 2005). Previous BEB studies have focused largely on timescales of months to a few years (Gallop et al., 2020; Harris et al., 2020; Vila-Concejo et al., 2010) and it is not known if BEBs can recover fully over longer timescales – or if erosion is a one-way process for some BEB settings, leading to progressive shoreline retreat (Harris et al., 2020). For example, sediments eroded from BEBs can be transported to nearshore sediment sinks, such as flood-tide deltas/shoals (Austin et al., 2018; Vila-Concejo et al., 2011; Vila-Concejo et al., 2007). In some cases these sediments can be returned to the beach (Austin et al., 2018; Jackson, 1995), but are sometimes permanently lost to the beach system. Beach sediment may be imported through alternate pathways like alongshore transport or offshore sources under certain conditions (Vila-Concejo et al., 2010).

BEBs can exhibit distinct behaviours and morphology following storms (Carrasco et al., 2012; Costas et al., 2005). For example, Eulie et al. (2017) show how backbarrier shorelines in the Albemarle-Pamlico estuary system in North Carolina (USA) have been retreating episodically due to storms since the 1950s, at a mean rate of 0.5 m/year. And Qiao et al. (2018) describe how 50 years of reclamation of low-lying estuarine shorelines in Shanghai (China) causes unwanted erosion of adjacent BEBs and low-lying coastal areas. Meanwhile, Gallop et al (2020) show both partial and full recovery of BEBs in New South Wales (Australia) following storm erosion. These studies highlight the tendency for slow or incomplete recovery of BEBs in contrast compared to open coast beaches. It appears that a fine balance exists between the frequency and severity of erosion and the rate of accretion leading to recovery. Moreover, there have been few studies of the influence of the often-extensive anthropogenic modifications on BEBs. The effects of anthropogenic intervention such as dredging, reclamation, seawalls and groynes alter BEB wave climate (Nordstrom, 1992), beach planform and shoreline positions (Lowe and Kennedy, 2016) and sediment source/sink pathways (Austin et al., 2018). For example, Carrasco et al. (2012) report decadal change to BEB shorelines in a barrier estuary in the Algarve (Portugal), which eroded up to 0.22 m/year due to the dredging of an adjacent navigation channel. Thus, changes to estuary/bay shorelines (natural or anthropogenic) can pose different complex coastal management and planning challenges.

To understand the long-term cycle of storm erosion and modal recovery for beaches in modified and natural estuaries and bays, we track shorelines on nine BEBs over decadal timescales. We have three objectives: (1) to develop a behavioural typology of decadal BEB shoreline evolution; (2) to determine the influence of proximal geomorphological features such as flood-tide deltas or river mouths, and the distance of BEB from ocean entrance; and (3) to assess the role of anthropogenic interventions on decadal BEB shoreline behaviour. This understanding of the evolution of BEBs over decadal scales is critical for effective coastal management and planning.

# 2. STUDY AREA

## 2.1. Climate

### *2.1.1. General wind, wave and tide conditions*

The Sydney region in SE Australia has NE prevailing winds with mean 9 am speed of 10.6 km/h. The region is microtidal with a mean spring tidal range of 1.25 m (Harley et al., 2017). The wave climate is swell dominated with moderate to high wave energy that typically originates from the S-SE ($\theta$ = 135°) and is characterised by mean offshore significant wave heights ($H_s$) of 1.6 m, mean periods ($T_z$) of 6 s and peak periods of 10 s ($T_p$) (Shand et al., 2010). Individual storms are defined as events with $H_s$ > 3 m (95$^{th}$ percentile $H_s$) for at least 6 hours, separated by at least 24 hours of gentle wave conditions (Shand et al., 2010). Storm clusters are groups of storms separated by less than a month, following Birkemeier et al. (1999). Storms occur year-round but are typically more common during Austral autumn and winter (April to August). Storms make landfall from a range of directions (NE to S) and are produced by mid-latitude cyclonic, low-pressure systems, extratropical low-pressure systems (East Coast Lows, ECLs) and lows to the east of Australia (Short and Trenaman, 1992). ECLs are a main source of extreme beach erosion and damage to coastal infrastructure on this coast (Harley et al., 2016). Storm frequency is controlled by Pacific climate patterns, including El Niño Southern Oscillation, Southern Annular Mode and Pacific Decadal Oscillation (Shand et al., 2010). Storm surges are typically small (< 0.7 m) due to the region's narrow continental shelf (Harley et al., 2017).

#### *2.1.2. Major storms*

The Sydney region has experienced 21 major storms (wave events) between 1941–2017 and of these storms (full details in Supplementary Table S1) those that eroded shorelines include:

- Cluster of two storms in June 1950 from NE–SE with remarkable rainfall, widespread flooding and substantial coastal erosion (Australian Bureau of Meteorology, 2015).
- Cluster of three storms in May–June 1974 from E–NE/E–SE, considered the most erosive event in the region since measured records began and damaging coastal infrastructure. This cluster had an estimated $H_s$ > 9 m, and an Average Recurrence Interval (ARI) of 50 years (Bryant and Kidd, 1975). Erosion was recorded in the Pittwater estuary at Snapperman and Great Mackerel beaches, and in Kamay (Aboriginal name for Botany Bay) along SW-facing BEBs

(Congwong, Currewol and Yarra Bay), damaging the newly constructed Port Botany Revetment Wall adjacent to Yarra Bay (Bryant and Kidd, 1975; Foster et al., 1975).

- Storm in December 1988 with remarkable rainfall impacted Pittwater causing substantial erosion to Great Mackerel (Cowell, 1989; Cowell and Nelson, 1991);
- Cluster of 5 ECLs in June 2007 primarily from SE caused 8 consecutive days of storm waves ($H_s$ > 3 m) and severe coastal erosion on Sydney's open coast beaches (Harley et al., 2016), and on the BEBs at Port Stephens, 230 km north of Sydney (Vila-Concejo et al., 2010).
- Cluster of 3 storms in July 2011 from ESE-SE eroded beaches along the regional coast (Gallop et al., 2020).
- Slow-moving ECL in June 2016 from E-NE when the highest waves $H_s$ > 6 m occurred during spring high tide, causing severe erosion on the open coast (Harley et al., 2017) and at Kamay and Pittwater (Gallop et al., 2020).

### 2.2. Sites

We focus on two estuaries in the Sydney metropolitan area in New South Wales, Australia (Fig. 1a). Both contain a broad range of BEBs (Fig. 1b-g; Table 1) with a variety of distances from estuary entrance, locations relative to flood-tide delta or river mouth, beach orientations, exposure to swell or wind waves, geological settings and anthropogenic interventions such as reclamation or groynes (Gallop et al., 2020).

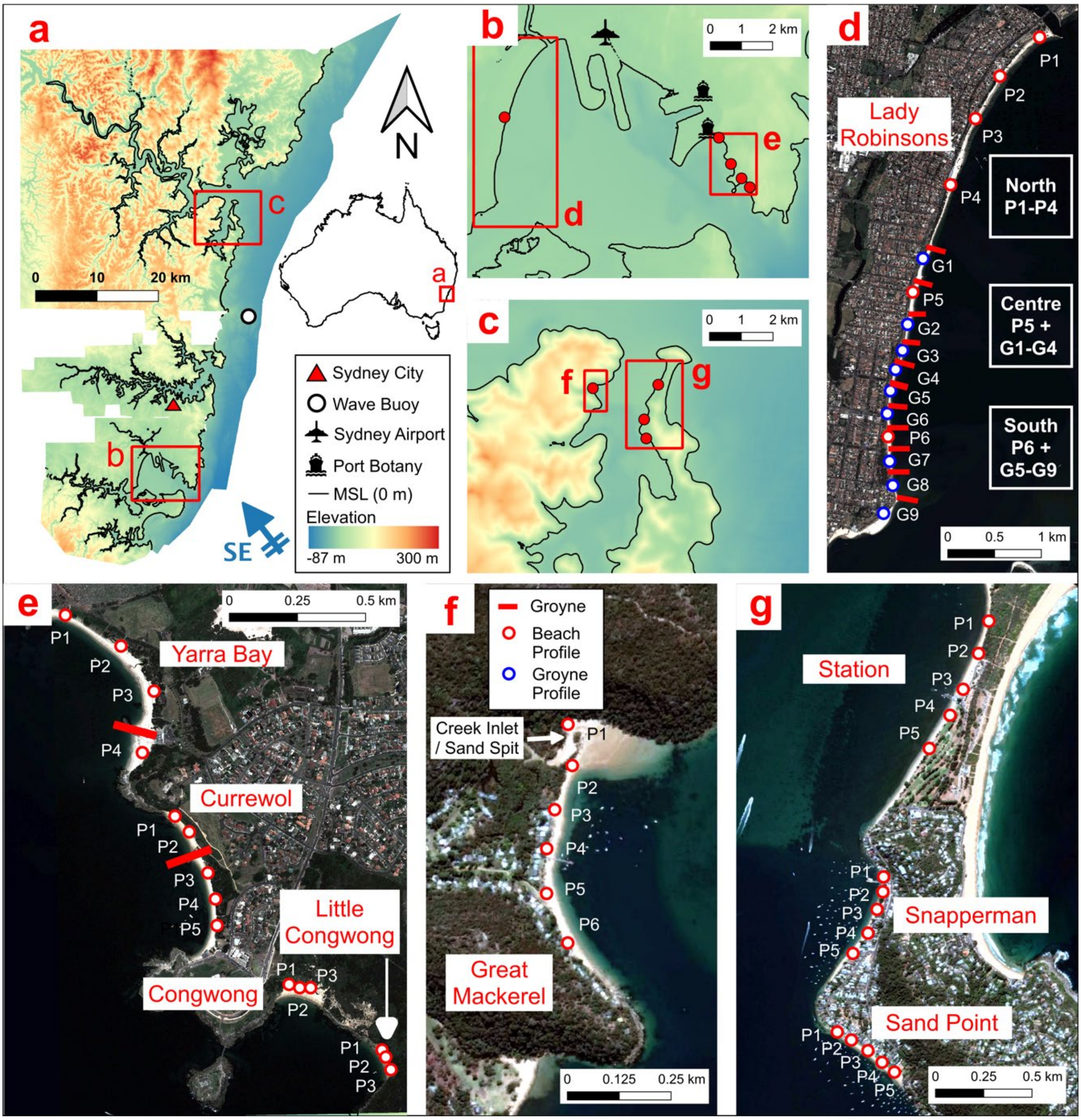


***Figure 1.*** *Study areas in (a) Australian and Sydney context showing (b) Kamay (Botany Bay) and (c) Pittwater with the Sydney offshore Waverider buoy (black/white circle). Kamay BEBs are (d) Lady Robinsons, (e) Yarra Bay, Currewol (Frenchmans), Congwong and Little Congwong. Pittwater BEBs are (f) Great Mackerel, (g) Station, Snapperman and Sand Point. BEBs have beach profiles (red/white circles), groyne profiles (blue/white circles) and groyne locations (red lines). Digital elevation models (a–c) are combined from Wilson and Power (2018a); Wilson and Power (2018b); Wilson and Power (2018c) and satellite images from Google Earth.*

*2.2.1. Pittwater estuary*

The Pittwater estuary (28 km north of Sydney) is a tide-dominated, drowned river valley (Roy et al., 2001), that forms part of the Broken-Bay-Hawkesbury-River estuary (Fig. 1a, c). Pittwater's entrance orientation is N–NE, and thus receives waves that propagate through the estuary entrance unmodified from the NE and refracted from the E-SE (Short, 1993). The estuary is 10 km long and 1 km wide and has an area of ~18.4 km$^2$ (OEH, 2018). The mean estuary depth is 9.9 m and the maximum depth is 22 m (OEH, 2018). The sediments are primarily sandy, with a flood-tide delta that extends ~2.5 km into the estuary. Seagrass meadows in the estuary are declining, since the 1940s (Cowell and Nelson, 1991). The net southward littoral drift within estuary through tidal channels along the western exposed shore and across the flood-tide delta is estimated at 1500 (±300) m$^3$/year between 1940–1990 (Kulmar and Gordon, 1987).

***Table 1:*** *Beach locations, beach length and orientation from Short (1993), entrance distance measured to the alongshore mid-beach location and beach/groyne profiles.*

| | BEB | Orientation | Beach Length (m) | Distance from Entrance (km) | Beach/Groyne Profiles |
|---|---|---|---|---|---|
| Pittwater | Great Mackerel | E | 640 | 1.9 | 5 (P2–P6) |
| | Station | NW | 1500 | 1.2 | 5 (P1–P5) |
| | Snapperman | NW | 640 | 2.2 | 5 (P1–P5) |
| | Sand Point | SW | 470 | 2.7 | 5 (P1–P5) |
| Kamay | Yarra Bay | SW | 680 | 2.6 | 4 (P1–P4) |
| | Currewol | W | 550 | 1.8 | 5 (P1–P5) |
| | Congwong | SE | 160 | 1.3 | 3 (P1–P3) |
| | Little Congwong | SW | 130 | 1.2 | 3 (P1–P3) |
| | Lady Robinsons | E | 5500 | 8.2 | 15 (P1–P6; G1–G9) |

We study 4 BEBs in the Pittwater estuary (Fig. 1c, f–g; Table 1). The embayed Great Mackerel Beach on the western shore is swash aligned and adjacent to the flood-tide delta and exposed to NE swell waves (Fig. 1f). It has a creek inlet (behind P2) that was artificially moved 100 m towards the northern headland in the late 1980s to protect oceanfront properties from shoreline retreat (Cowell and Nelson, 1991). On the eastern shore we focus on three drift-aligned beaches, Station Beach is on the backshore of a sand barrier (shared with the open coast Palm Beach) (Fig. 1g). Further south is Snapperman Beach, which lies north of a low-lying promontory and adjacent to the flood-tide delta and a nearshore tidal channel; it has a partial seawall and is backed by residential properties (Fig. 1g). Sand Point BEB occupies the south side of the same promontory, has a partial seawall and is also backed by residential properties (Short, 1993).

### *2.2.2. Kamay*

The naturally and culturally significant Kamay (Botany Bay) is a marine-dominated open embayment (Roy et al., 2001) 12 km south of Sydney (Fig. 1a–b). Kamay occupies ~39.6 $km^2$ and has a maximum width and length of 5 km and 8 km. The average depth is 11.4 m and the bay has a SE-facing entrance that is 1.1 km wide (OEH, 2018). Two rivers enter Kamay: The Cooks River in the NW of the estuary and the Tucoerah (Aboriginal name for Georges River) in the SW (Fig. 1b). The estuary is composed primarily of sandy sediments with some mud around the extensive mangrove habitats on the southern shore (Jones, 1981). The estuary has been heavily modified since the 1940s (Fig. 2), including river realignment, dredging and reclamation to build and extend the port and airport (Fig. 1b), alongside ongoing maintenance dredging and beach nourishment/stabilisation with groynes, rock armament and revetments.

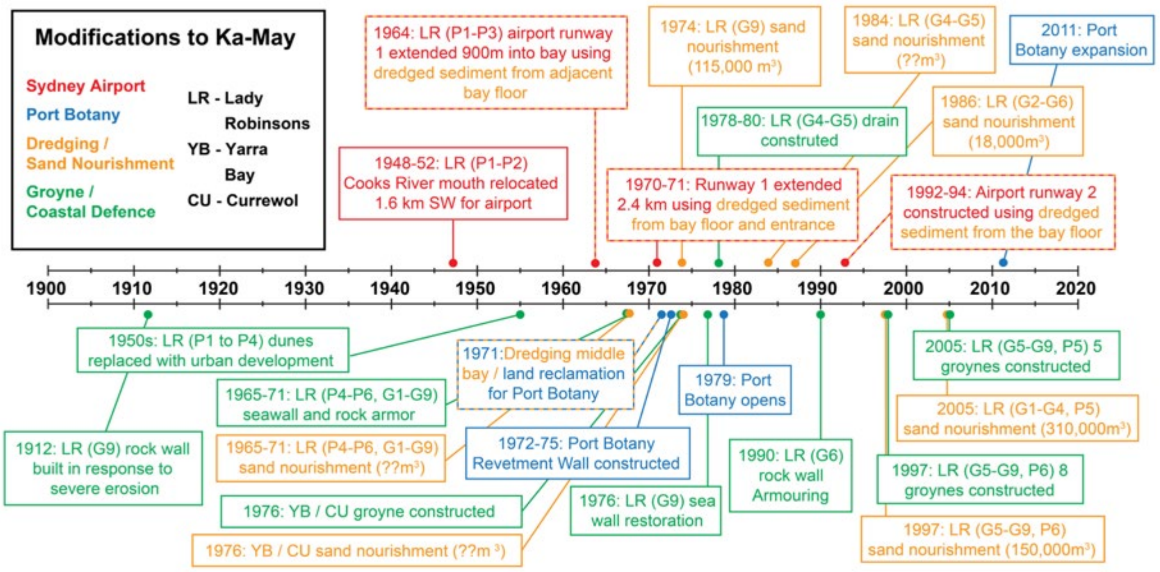


***Figure 2:*** *Timeline of anthropogenic intervention in Kamay from 1900. BEB and profile locations are coloured by intervention type (red/blue/yellow/green or multiple). Collated from Aijaz and Treloar (2003); Bryant and Kidd (1975); Cowell and Kannane (2000); Davies and McIlquham (2011); Frost (2011); Jones (1981).*

We studied 5 BEBs in Kamay, including Congwong, Little Congwong, Currewol (Aboriginal name for Frenchmans Bay) and Yarra Bay on the NE shore near the entrance and Lady Robinsons on the western shore (Fig. 1d–e; Table 1). Congwong and Little Congwong are swash-aligned pocket beaches inside a larger embayment. They are both backed by well-developed dunes and being the closest to the entrance, are exposed to S–SE swell waves (Short, 1993). Currewol and Yarra Bay, also swash aligned, have low-lying vegetated dunes and Yarra is adjacent to the Port Botany Revetment Wall (Fig. 1b, e). These 2 BEBs are west-facing and each have a central groyne built in 1976 (Cowell and Kannane, 2000). Lady Robinsons, which is drift-aligned, is bound by the Cooks and Tucoerah Rivers (Fig. 1d). This beach is at the front of a prograding barrier that is heavily modified and adjacent to the airport in the north. Groynes were constructed along the central and southern beach in 1997 and 2005 (Cowell and Kannane, 2000) (Fig. 1d; Fig. 2).

## 3. METHODS

### 3.1. Image Georeferencing

We used a total of 100 images to form a shoreline timeseries at sub-decadal intervals (Fig. 3; Supplementary Table S2). There were 33 vertical aerial images and 19 satellite images between 1941 and 2017 for Pittwater, and 40 vertical aerial images and 8 satellite images between 1943 and 2017 for Kamay. Aerial images were geo-rectified in Pittwater to a 2017 satellite image (NearMap Australia Pty Ltd), and to a 2014 Orthoimage for Kamay (Department of Planning, Industry and Environment, NSW Government). We followed standard methodology ensuring the highest number of fixed ground control points (GCPs) (Novak, 1992) using permanent fixed features such as buildings, road intersections, jetties and geologic structures. We used 10–25 GCPs per image (mean 11), depending on image resolution and identifiable features, to perform a 2nd degree polynomial transformation (Rocchini et al., 2012). We calculated root mean square error (RMSE), which corresponds to the sum of residual distances between the location specified for a GCP and the place where it ends up after the transformation (Rocchini et al., 2012). RMSE values were 0.5–5 m at Pittwater and 1.5–9.8 m at Kamay (mean = 3.5 m).

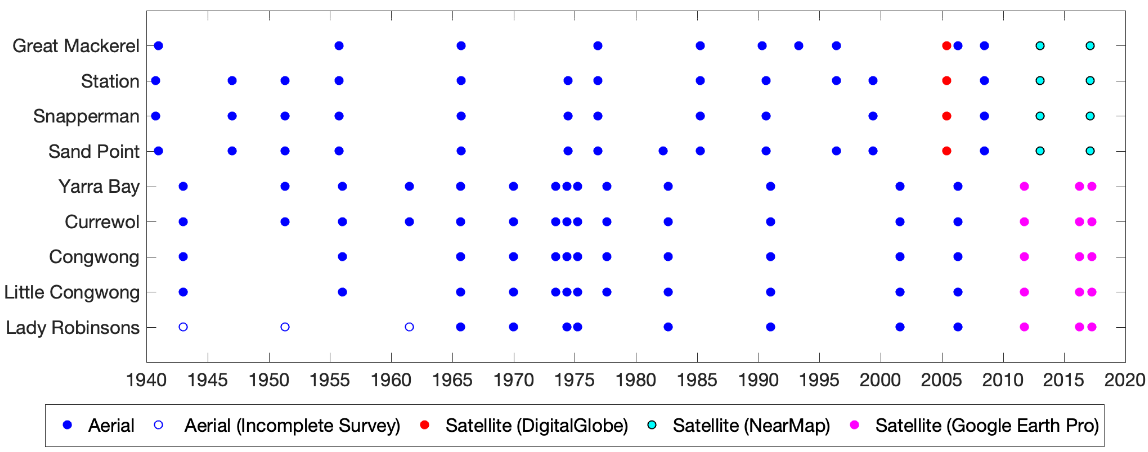


***Figure 3:*** *Timeseries of aerial and satellite imagery and sources used in this study to track shorelines.*

### 3.2. Decadal Shoreline Analysis

We defined the shoreline as the high-water line (HWL) due to the clear contrast between wet and dry sand in historical images, identified as a consistent shoreline indicator by Boak and Turner (2005). In this region there is limited seasonal shoreline variability for both open coast (Harley et al., 2016) and estuarine beaches (Kennedy, 2002), so infrequent (decadal) images are taken as representative of conditions that year. Uncertainty in shoreline measurements include an error of 6 m associated with tidal variability, estimated from a mean beach gradient of 10 degrees (Gallop et al., 2020) and spring tidal range of 1.25 m. This is combined with an error of 3 m for onscreen delineation following Ruggiero et al. (2003), and the mean RMSE of 3.5 m. The total uncertainty of 7.5 m was calculated following Ruggiero et al. (2003) as the root sum squared of the 3 individual error terms.

Beach width was measured from a profile with origins at the back-beach (seawall or dune toe) to the shoreline identified in each image. The profiles are shore normal and numbered alongshore from north to south (Fig. 1d–g; Table 1). Each of the 41 profiles labelled with P (e.g., P1) in Figure 1 matches Gallop et al. (2020). We also measured 9 groyne profiles with labelled with G (e.g., G1) located at the midpoint between groyne pairs along the central and southern sections of Lady Robinsons in Kamay (Fig. 1d). To determine decadal behaviour based on storm erosion and recovery we define the BEB recovery timescale $t_r$, which is a function of the amount of sediment eroded during a storm $E_s$ and the rate accretion between storms $A_r$, and compare this with storm return timescales $t_{st}$.

### 3.3. Offshore wave data

We used offshore wave data for the Sydney region between 17/07/1987 and 31/07/2017 from a Waverider buoy located approximately 10 km offshore, at 90 m water depth (Fig. 1a). The buoy is 22 km south of the Pittwater entrance and 30 km north of the Kamay entrance. We used hourly measurements of $H_s$, maximum wave height ($H_{max}$), $T_z$, $T_p$ and $\theta$. Hourly measurements were processed to provide daily and 7-day moving averages and deep-water wave power ($P$) was calculated following Komar (1998) as:

$$P = EC_g \tag{1}$$

where wave energy ($E$) is expressed as

$$E = \frac{1}{16} pgH_s^2 \tag{2}$$

where $p$ is seawater density (1025 kg/m$^3$), $g$ is gravitational acceleration (9.81 m/s), and wave group velocity ($C_g$) is expressed as

$$C_g = \frac{gT_z}{2\pi} n \tag{3}$$

where deep-water $n$ is 0.5. Storms were identified using a Peaks-Over-Threshold method described in Harley (2017) using $H_s$ = 3 m, for a minimum on 6 hours (Shand et al., 2010). Finally, based on storm wave direction (available since 03/03/1992) and entrance headland orientations we determined the overall estuary exposure to storms as the number of storms that had wave directions that could propagate through each entrance.

# 4. RESULTS

## 4.1. Storm wave exposure

There were 481 storms during the study period; 427 of which occurred between 1992 and 2017 when wave direction measurements were available (Fig. 4). Mean storm statistics were a duration of 33 hours, $H_s$ of 3.55 m, $T_z$ of 7.6 s, $T_p$ of a 10.8, $\theta$ of 158º and total storm power of 1350 Kw/m or ~40 Kw/m/hour (Fig. 4). The Kamay entrance faces SE (~135 degrees) and is 1.1 km wide, so 380 storms (89%) had waves that could propagate through giving a mean annual storm-exposure rate of 14.5 storms/year (Fig. 5). Conversely, the Pittwater Estuary entrance faces N–NE (~25 degrees) and is 1 km wide, so only 37 storms (9%) storms could propagate through, giving a mean annual storm-exposure rate of 1.5 storms/year. Therefore, BEBs inside Kamay are potentially exposed to 10 times more storms than in Pittwater (Fig. 5).

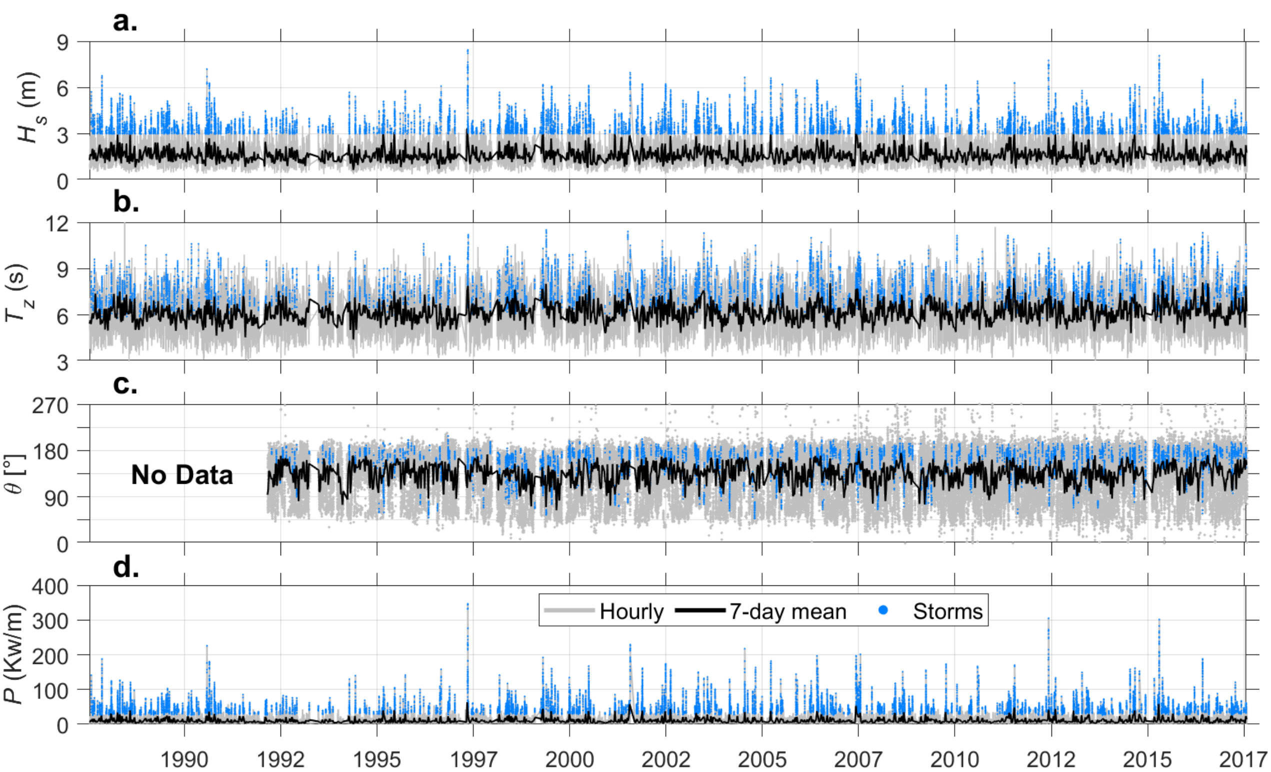


***Figure 4:*** *Sydney offshore wave data from 1987 to 2017, hourly (grey), 7-day mean (black) and storms (light blue) measurements. (a) Significant wave height ($H_s$), (b) wave period ($T_t$), (c) wave direction ($\theta$) and (d) wave power energy flux (P).*

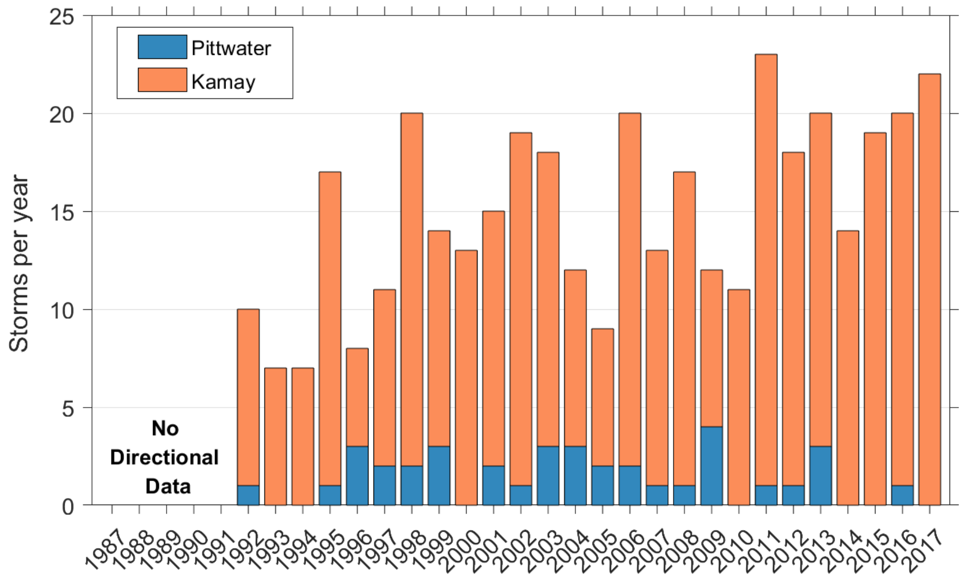


***Figure 5:*** *Number of storm events per year with storm wave directions that could pass directly through the entrances of Pittwater (blue) and Kamay (orange).*

## 4.2. PITTWATER SHORELINE ANALYSIS

### 4.2.1. Western Shore: Great Mackerel

Great Mackerel is the most swell-exposed BEB in Pittwater, being near the entrance and on the western shore in-line with the entrance (Fig. 1f). This beach exhibited the greatest decadal variability in beach width of the 4 Pittwater BEBs (Fig. 6a; Fig. 7a). Following the 1974 storm cluster, beach width was reduced up to 18 m (39% pre-storm beach width) and the northern creek inlet (adjacent to P1) migrated ~100 m south towards P2 (Fig. 6a). These storms permanently narrowed the beach at P2 (by up to 40 m), from a maximum in the mid-1950s. A storm in late 1988 again reduced width by up to 19 m (53% beach width) and substantial localised flooding was recorded (Supplementary Table S1). Following this, the beach continued to narrow, decreasing by 15 m in the 1990s, 10 m in the early 2000s (Fig. 6a; Fig. 7a) then a further 8 m r (< 67% beach width), aided by storms in 2007, 2012 and 2016. Some recovery occurred between storms: almost complete recovery occurred 11 years after 1974 storms, only partial recovery 6 years following the 1988 storm, and partial recovery 5 years after

2011 storms (Fig. 7a). However, the general trend at Great Mackerel was a net loss between 1941 and 2017 as the recovery timescale ($t_r$) was longer than the storm return timescale ($t_{st}$) – widths decreased between 5 and 33 m (mean 0.24 m/year), faster at north (P2) and south (P5–P6) ends than mid-beach (P3) (Fig. 7a; Table 2).

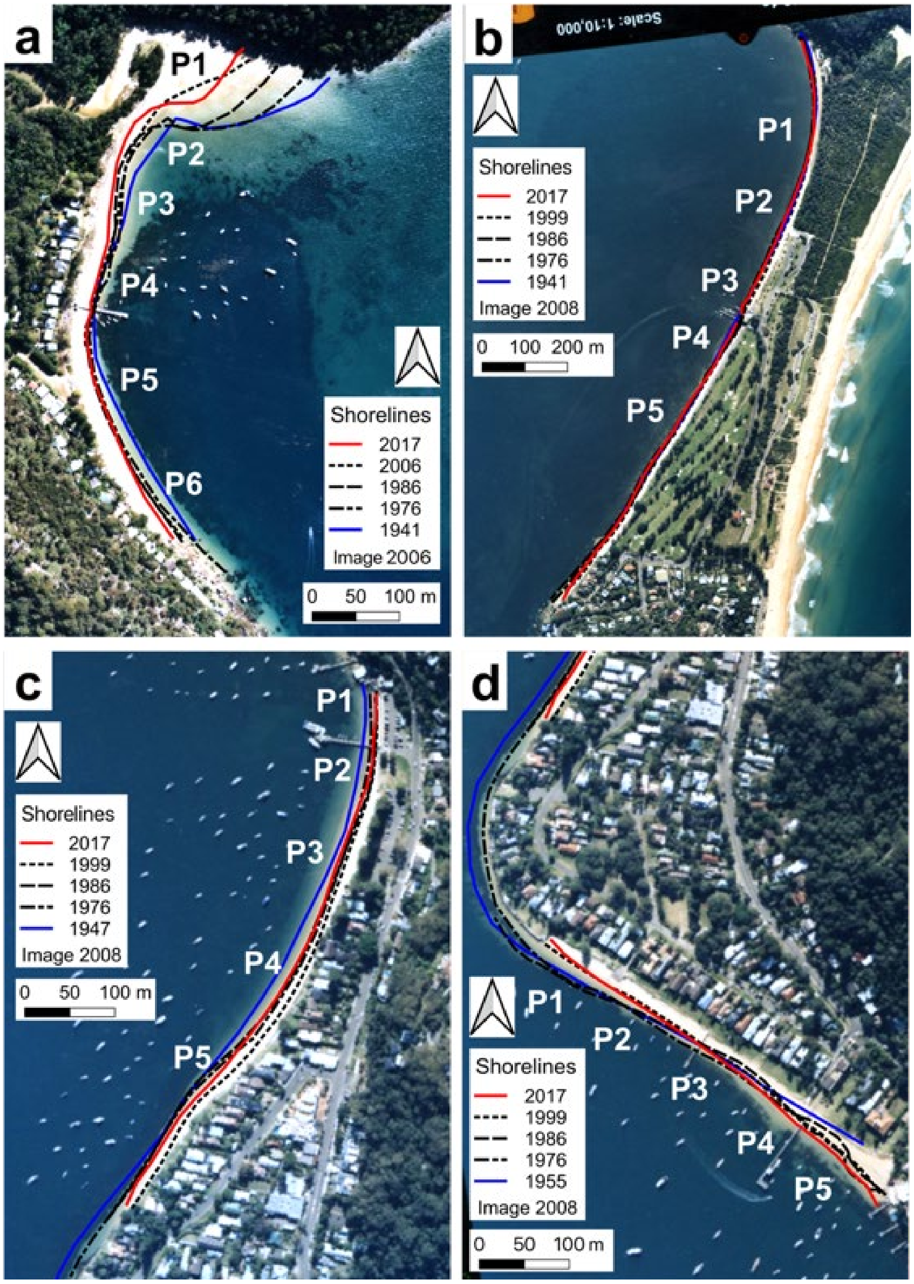


***Figure 6**: Pittwater estuary beaches (a) Great Mackerel, (b) Station, (c) Snapperman and (d) Sand Point showing the first, last and ~10 yearly shorelines, with beach profiles labelled.*

#### 4.2.2. Eastern Shore: Station, Snapperman and Sand Point

Station Beach is a backbarrier beach and the closest to the entrance on the eastern shore (Fig. 1g; Fig. 6b; Fig. 7b). Shoreline erosion occurred in the early 1950s of up to 8 m (40% of the pre-storm beach width), in 1974 up to 12 m (55% of the pre-storm beach width), in 1998 up to 11 m (42% of the pre-storm beach width), in 2007 up to 6 m (32% of the pre-storm beach width) and in 2016 up to 7 m (37% of the pre-storm beach width) (Fig. 6b; Fig. 7b). Notably, recovery took 5 years following the 1950s storms, 3 years following the 1974 storms, up to 10 years following the 1998 storm and the beach was partially recovered after the 2011 storms and before the 2016 storm (Fig. 7b). However, the overall net change in beach width for P1–P4 was negligible (within error) with the recovery timescale ($t_r$) shorter or equal to storm return timescale ($t_{st}$) – while the southern end (P5) increased width by 18 m (0.23 m/year) (Fig. 7b; Table 2).

Snapperman beach widths did not change much (Fig. 1g; Fig. 6c; Fig. 7c). Between storms in 1955 and 1974 the beach width reduced by up to 23 m (P3–P5) (Fig. 7c). Following this, the central and south beach widths reduced by up to 11 m (22% of the pre-storm beach width) in 1974. The beach width reduced by up to 18 m (72% of the pre-storm beach width) in 1998 storm, by up to 7 m in 2007 storm (100% of the pre-storm beach width) and by up to 7 m (88% of the pre-storm beach width) in 2016 storm (Fig. 6c; Fig. 7c). Recovery took 5 years following the 1950 storms, 3 years following the 1974 storms, was incomplete in 10 years following the 1988 storm, 11 years following the 1998 storms and was partial 5 years after the 2011 storms (Fig. 7c). However, the overall net change in beach width was negligible (P3–P5) and therefore the recovery timescale ($t_r$) was shorter or equal to storm return timescale ($t_{st}$) – except at the northern end (P1–P2) where width was reduced up to 17 m (0.22 m/year) (Fig. 7c; Table 2).

***Table 2:** Net BEB width change (rate of change) m (m/year) between 1941 (Pittwater)/1943 (Kamay) and 2017 and before (*) and after groyne construction (**). Positive indicates beach widening and negative indicates beach narrowing and bold values are changes above the method uncertainty (7.5 m). '†' denotes change from 1965 (first image) at Lady Robinsons G8–9.*

| | BEB | P1 | P2 | P3 | P4 | P5 | P6 |
|---|---|---|---|---|---|---|---|
| Pittwater | Great Mackerel | - | **-33.0 (-0.43)** | **-19.0 (-0.25)** | -5.0 (-0.07) | **-11.0 (-0.14)** | **-24.0 (-0.32)** |
| | Station | -3.0 (-0.04) | -3.0 (-0.04) | -2.0 (-0.03) | **-8.0 (-0.11)** | **17.6 (0.23)** | - |
| | Snapperman | **-11.0 (-0.14)** | **-17.0 (-0.22)** | -6.0 (-0.08) | -4.0 (-0.05) | -4.0 (-0.05) | - |
| | Sand Point | 4.0 (0.05) | 7.0 (0.09) | **12.0 (0.16)** | **22.0 (0.29)** | **29.0 (0.38)** | - |
| Kamay | Yarra Bay | -4.8 (-0.06)<br>**-29.0 (-0.88)***<br>**17.1 (0.42)**** | **30.3 (0.41)**<br>**16.4 (0.50)***<br>3.6 (0.09)** | **61.1 (0.83)**<br>**59.5 (1.80)***<br>1.0 (0.02)** | **51.3 (0.69)**<br>**8.1 (0.25)***<br>**41.6 (1.01)**** | - | - |
| | Currewol | **-11.5 (-0.16)**<br>**-15.8 (-0.48)***<br>-1.6 (0.04)** | 0.8 (0.01)<br>**-30.9 (-0.93)***<br>2.8 (0.07)** | -2.1 (-0.03)<br>**-9.1 (-0.28)***<br>5.0 (0.12)** | **-13 (-0.18)**<br>**-8.9* (-0.27)**<br>-5.6** (-0.14) | **-7.8 (-0.11)**<br>3.1 (0.09)*<br>-5.3 (-0.13)** | - |
| | Congwong | **10.6 (0.14)** | **10.8 (0.15)** | **10.3 (0.14)** | - | - | - |
| | Little Congwong | 2.3 (0.03) | 1.9 (0.03) | 3.2 (0.04) | - | - | - |
| | Lady Robinsons (Profiles) | **59.8 (0.81)** | **15.9 (0.22)** | **3.80 (0.05)** | **24.5 (0.33)** | **10.4 (0.14)**<br>**-29.8 (-0.48)***<br>-6.0 (-0.50)** | **10.0 (0.14)**<br>2.7 (0.05)*<br>3.0 (0.15)** |
| | | **G1** | **G2** | **G3** | **G4** | **G5** | **G6** |
| | Lady Robinsons (Groynes) | **12.9 (0.17)**<br>**-9.0 (-0.14)***<br>2.5 (0.21)** | 5.8 (0.08)<br>**-25.4 (-0.41)***<br>**-11.9 (-0.99)**** | **-13.2 (-0.18)**<br>**-10.2 (-0.16)***<br>**-30.1 (-2.51)**** | 5.0 (0.07)<br>-2.9 (0.05)*<br>**-21.4 (-1.79)**** | **-8.9 (-0.12)**<br>-2.3 (-0.04)*<br>**-13.9 (-0.69)**** | **-11.1 (-0.15)**<br>**-14.7 (-0.27)***<br>**-18.2 (-0.91)**** |
| | | **G7** | **G8** | **G8** | - | - | - |
| | | **-21.0 (-0.28)**<br>**24.2* (-0.45)***<br>-5.4* (-0.27)** | **-24.9 (-0.48)†**<br>**-15.4 (-0.48)†***<br>**-40.8 (-2.04)**** | **31.7 (0.61)†**<br>**8.2 (0.26)†***<br>2.6 (0.13)** | - | - | - |

Sand Point is the furthest (~2.7 km) from the Pittwater entrance (Fig. 1g). Despite this, there was a significant shoreline response to storms (Fig. 6d; Fig. 7d). This beach was impacted by the 1950 storm cluster when the beach rotated clockwise, reducing width by 6 m (18% of the pre-storm beach width) in the north (P1) and increasing width by 8 m (20% beach width) in the south (P5) (Fig. 7d). The 1974 storms reduced widths along the entire beach, by up to 12 m (29% of the pre-storm beach width). The beach width was then stable from the late-1970s until the 1998 storms when beach widths were reduced by up to 8 m (16% of pre-storm beach width) and again in 2011 by up to 11 m (100 % of pre-storm beach width) at the north end (Fig. 7d). Unlike the other Pittwater beaches, beach width was not noticeably impacted by the storms in 1988, 2007 or 2016. Beach recovery took up to 5 years following the 1950 storms, 3 years following the 1974 storms and recovered following the 2011 storms before the 2016 storm (Fig. 7d). Overall, Sand Point was stable with a recovery timescale ($t_r$) shorter or equal to storm return timescale ($t_{st}$), however the shoreline rotated clockwise: at northern end (P1–P2) it narrowed by up to 7 m (0.09 m/year) while at central and southern sites (P3–P5) it prograded by 29 m (0.38 m/year) (Fig. 7d; Table 2).

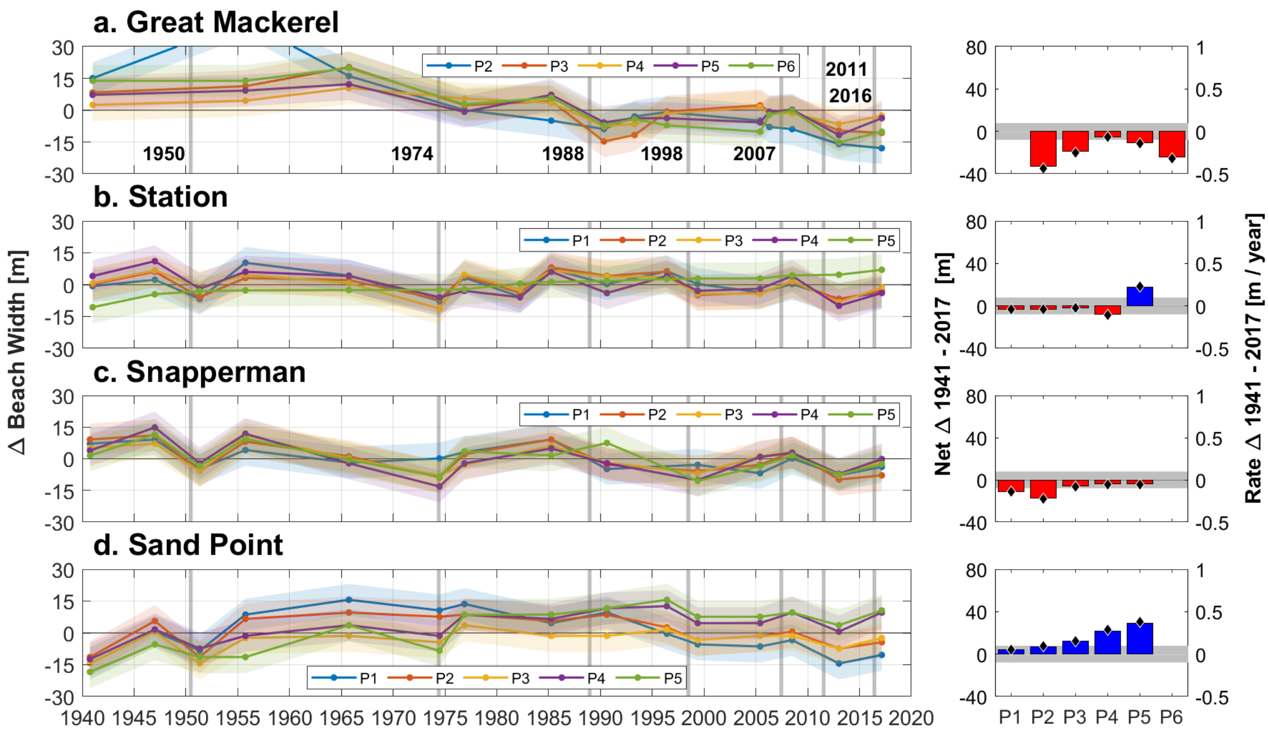


*__Figure 7__: (left) Timeseries of beach width (difference from mean) at (a) Great Mackerel, (b) Station, (c) Snapperman and (d) Sand Point (right) Net change in beach width (m) between 1941 and 2017 is shown as net increase (blue) and decrease (red), and annual rates of change (m/year) (black diamonds). The shaded areas in all plots represent the total uncertainty (7.5 m) and notable storms are shown by the vertical grey lines (Supplementary Table S1).*

## 4.3. KAMAY SHORELINE ANALYSIS

### 4.3.1. Northeast Shore: Yarra Bay, Currewol, Congwong and Little Congwong

Yarra Bay on the northeast shore of Kamay, adjacent to the Port Botany Revetment Wall, exhibited notable decadal variability (Fig. 1e; Fig. 8a; Fig. 9a). In the 1940s the southern half of the Yarra embayment (P3–P4) had limited or no sediment with underlying rocks exposed; in comparison, the northern beach (P1–P2) had ample sediment (Fig. 8a). By the 1960s the beach had started to accrete at the southern end, although some rocks were still exposed between P3 and P4. By the mid-1970s, following dredging for the port and the 1974 storms, the beach underwent extreme erosion at the northern end (P2), with widths reduced by up to 23 m (90% of the pre-storm beach width) and erosion encroached into the dunes (Fig. 2; Fig. 9a). These impacts led to clockwise shoreline rotation, with the northern end narrowing and the southern end widening (Fig. 9a). Following the damaging 1974 storms the beach recovered partially in the 2 years (P1) prior to the groyne construction and sand nourishment in 1976 (Fig. 2; Fig. 9a). Other notable storm erosion and recovery responses were masked by anthropogenic interventions and a recovery timescale ($t_r$) that was shorter or equal to storm return timescale ($t_{st}$) (Fig. 8a). The overall trend (1943–2017) was accretional with widths increasing by up to 60 m (0.83 m/year) closest to the groyne (Fig. 8a; Table 2).

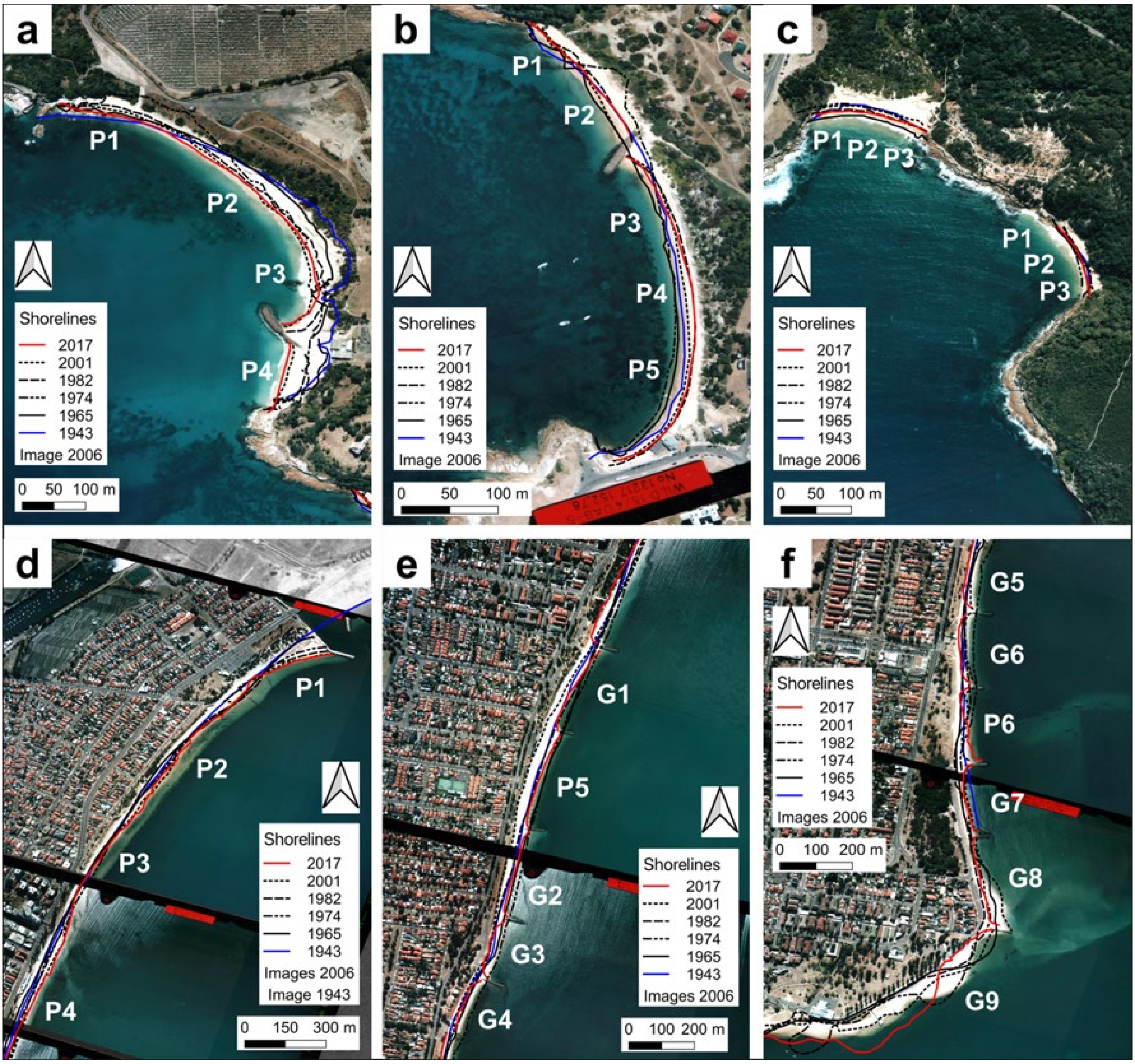


***Figure 8:*** *Decadal shorelines in Kamay with the first, last and ~10 yearly shorelines are shown, and profiles are labelled. (a) Yarra Bay, (b) Currewol, (c) Congwong (left) and Little Congwong (right), Lady Robinsons North (d), Central (e) and South (f). The red squares are watermarks.*

At Currewol, the northern end (P1–P3) is more exposed to waves propagating through the entrance and exhibited larger changes in beach width than the more-sheltered southern end (P4–P5) (Fig. 1e; Fig. 8b; Fig. 9b). Following storms in the early 1950s beach widths were reduced by up to 12 m (61% of the pre-storm beach width), and again by up to 6 m (31% of the pre-storm beach width) after the 1974 storms. Following the 1974 storms, the shoreline rotated clockwise from P1 to P5 with the northern profiles narrowing by up to 20 m (211% of the pre-storm width) and caused expansive erosion to the dunes (Fig. 9b). There was limited or no recovery in the following 2 years (Fig. 8b). This prompted the construction of a groyne and nourishment in 1976, similar to Yarra Bay (Fig. 2). The beach was stable after these interventions, until the 2007 and 2011 storm clusters combined reduced widths up to 9 m (38 % of pre-2007 storms beach width). Recovery to pre-2007 widths took up to 9 years (Fig. 9b). Overall changes in beach width (1943–2017) saw the northern (P1) and central-south beach (P4) reduced up to 13 m (-0.18 m/year), while the centre beach (P3) was negligible (Fig. 9b; Table 2) suggesting recovery timescale ($t_r$) is shorter or equal to storm return timescale ($t_{st}$).

Congwong and Little Congwong are the most exposed BEBs in Kamay and shorelines at both beaches showed little change, fluctuating by ±10 m with recovery timescale ($t_r$) shorter or equal to storm return timescale ($t_{st}$) (Fig. 1e; Fig. 8c; Fig. 9c–d). These BEBs were impacted by the 1974 storm cluster when Congwong eroded by up to 6 m (31% of the pre-storm beach width) and Little Congwong accreted by up to 12 m (76% pre-storm beach width); the shoreline also rotated clockwise from north to south at Little Congwong (Fig. 9c–d). The 1950, 1998, 2007 2012 and 2016 storms caused negligible responses. Following the 1974 storms, Congwong recovered 50% of widths within a year and both BEBs had recovered fully in 3 years (Fig. 9c–d). The overall trend (1943–2017) at Congwong had widths increased up to 10 m (0.14 m/year), while at Little Congwong net change was negligible (Fig. 9c–d; Table 2).

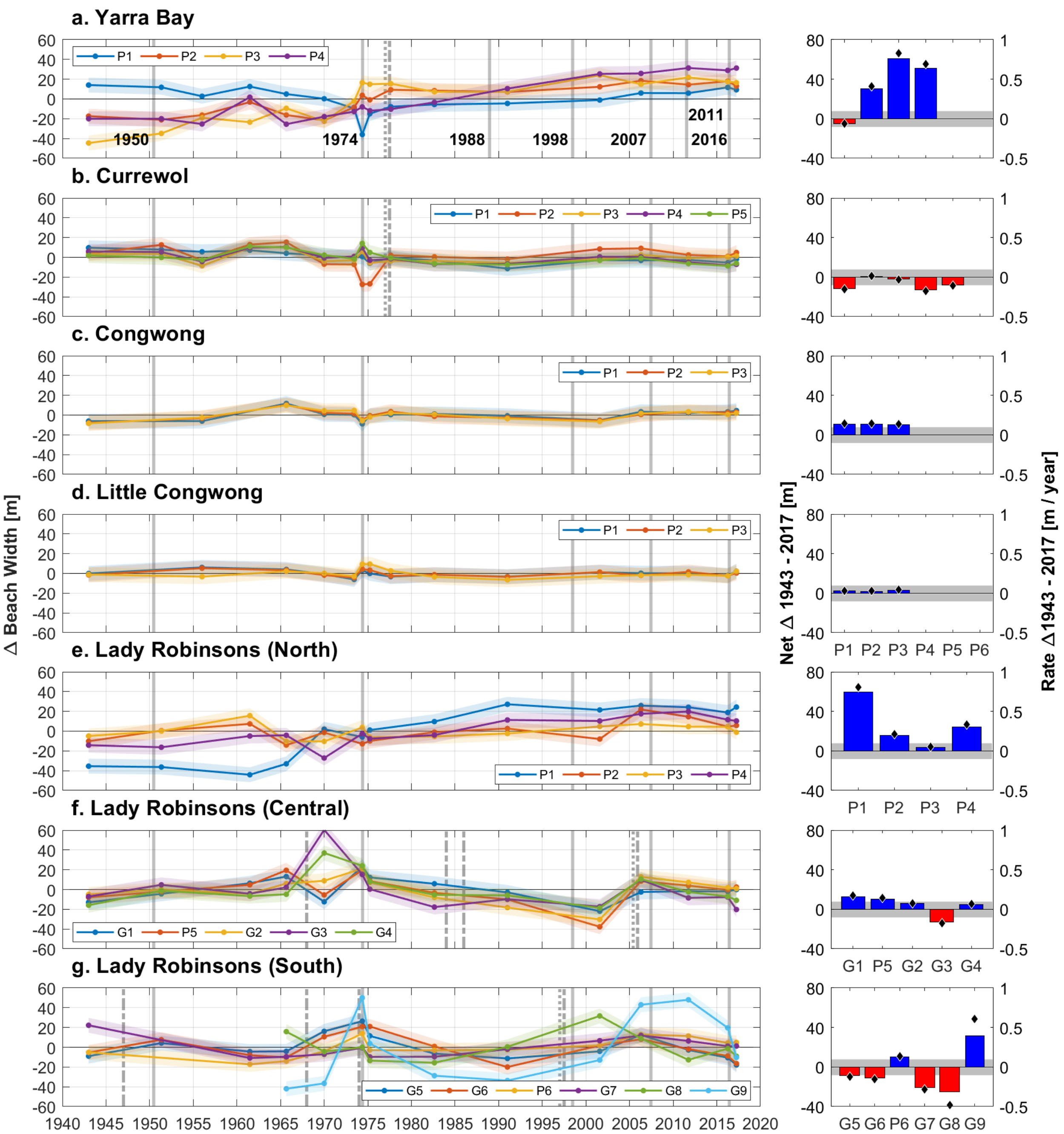


***Figure 9****: (left) Timeseries of beach width (difference from mean) for (a) Yarra Bay, (b) Currewol, (c) Congwong, (d) Little Congwong and Lady Robinsons north (e), central (f) and south (g). (right) Net change in beach width (m) between 1943 and 2017 with net increase (blue) and decreases (red), and rates of change (m/year) (black diamonds). Note the shaded areas in both the left and right plots represent the total uncertainty (7.5 m), notable storms (solid grey lines) (Supplementary Table S1), groyne construction (grey dotted lines), sand nourishment (grey dot-dash lines) and the net rates for G8 and G9 in (g) were calculated between 1965 (first image) and 2017.*

### 4.3.2. Western Shore: Lady Robinsons

Lady Robinsons is the farthest from the estuary entrance (8.2 km) and has the most anthropogenic interventions (Fig. 1d; Fig. 9e–g). There were significant differences in shoreline behaviour between the northern, central and southern sections. The northern section (P1–P4) accreted overall (1943–2017) with beach widths increasing by up to 60 m (0.81 m/year), while the shoreline rotated clockwise P1 to P4 (Fig. 8d; Fig. 9e; Table 2). The 1974 storm cluster impacted the beach (P3) narrowing it by 10 m (44% of the pre-storm width) (Fig. 9e). The profiles affected by these storms were accreted before the storms and did not recover to pre-1974 widths until 1990. Subsequent storms did not impact this section due to the airport runway extensions (Fig. 2; Fig. 9e).

The beach widths on the central section of Lady Robinsons (P5, G1–G4) continually narrowed requiring intervention (Fig. 1d; Fig. 9f). This section was eroded following the 1974 storms by 11 m (19% pre-storm beach width) and then continued to lose sand coinciding with dredging for the runways in the 1990s (Fig. 2); these losses were reversed when groynes were constructed in 2005 (Fig. 8e; Fig. 9f). The 2007 and 2011 storm clusters and the 2016 storm further eroded this section with limited recovery recorded by the end of this study, suggesting recovery timescales ($t_r$) are longer than the storm return timescale ($t_{st}$) (Fig. 9f). Although the storms and dredging reduced beach widths, repeated sand nourishment increased the net beach width (1943–2017) up to 12.9 m/year (0.17 m/year), although this is not the case at G3 which had overall width reduced by 13.2 m/year (0.18 m/year) (Fig. 2; Fig. 9f; Table 2).

Beach widths in the southern section (P6, G5–G9) were characterised by large shoreline fluctuations and decadal shoreline retreat that were mitigated by four sand nourishment interventions in 1943, 1964, 1971 and 1997 (Fig. 1d; Fig. 2; Fig. 9g). The 1974 storms reduced beach width by up to 17 m (80% of the pre-storm beach width) with only one profile recovering 15 years later (G8) (Fig. 9g). Groynes were built in 1997 to stabilise this section, however the 2007, 2011 and 2016 storms again eroded this section with no recovery between storms, suggesting recovery timescales ($t_r$) in this section were longer than the storm return timescale ($t_{st}$) (Fig. 9g). Shorelines between the groynes had anti-clockwise orientations (Fig. 8f), indicating southward longshore transport. Overall change in beach width (1943–2017) was varied, with the southernmost site (G9) accreted 30 m (0.61 m/year) while the adjacent beach (G8) eroded by 24.9 m (-0.48 m/year) (Fig. 8f; Table 2).

# 5. DISCUSSION

## 5.1. Decadal behaviours of BEB shorelines

Considerable erosion of BEBs occurred during storms when ocean swell waves propagated through the entrances of semi-enclosed estuaries. During low-energy wave conditions between storms, transport of sand back onto beaches was slow and post-storm recovery took years. In previous work (Costas et al., 2005; Gallop et al., 2020; Harris et al., 2020; Nordstrom and Jackson, 2012), incomplete recovery was observed over months to several years, while here we show that some BEBs can recover fully after storms, given enough time (Fig. 9c, f and 10). The level of BEB recovery depends on the recovery time relative to the return time of storms. When storms occur frequently or at beaches where recovery time is slow, the recovery timescale ($t_r$) may be longer than the storm return timescale ($t_{st}$) and recovery will be incomplete. Our results include BEB shorelines where $t_r > t_{st}$ and others where $t_r < t_{st}$ or $t_r \sim t_{st}$, representing different decadal-scale behaviours (Fig. 7; Fig. 9; Fig. 10). Based on the BEBs in this study (Fig. 10; Table 3), we propose a decadal behavioural typology of BEB shorelines: *prograding*, *quasi-stable, retreating* and *relict* BEBs. Where $t_r < t_{st},$ beaches recover between storms as they do on the open coast; these *quasi-stable* BEBs show limited decadal-scale change. They may occur where beaches are entirely sheltered from storm waves (Currewol post-1974) or exposed to significant wave energy between storms and available sediment sources (e.g., Congwong and Little Congwong, Fig. 9b–c). This supports Costas et al. (2005) who suggest that wave exposure is vital for any beach recovery. However, where $t_r > t_{st}$, beaches cannot recover before the next erosion event; these *retreating* BEBs exhibit partial recovery between storm events (e.g., Great Mackerel). Some beaches exhibited negligible recovery between storms (Table 3) – these *relict* BEBs (e.g., Lady Robinsons south) appear unrelated to modal conditions (relict) and reflect prior storm erosion. These BEBs may have formed under different environmental conditions and, without further intervention, could eventually disappear under contemporary conditions. Finally, we also observed *prograding* BEBs (e.g., Sandy Point, Lady Robinsons north). Although the mechanisms and sediment sources for this behaviour are unknown (Gallop et al., 2020), reduced swell exposure (far removed from ocean entrance) and alongshore transport are likely factors in this progradation (Fig. 7d; Fig. 9d). As for *relict* BEBs, these *prograding* BEBs may also reflect environmental change (i.e., local sediment budget has been altered).

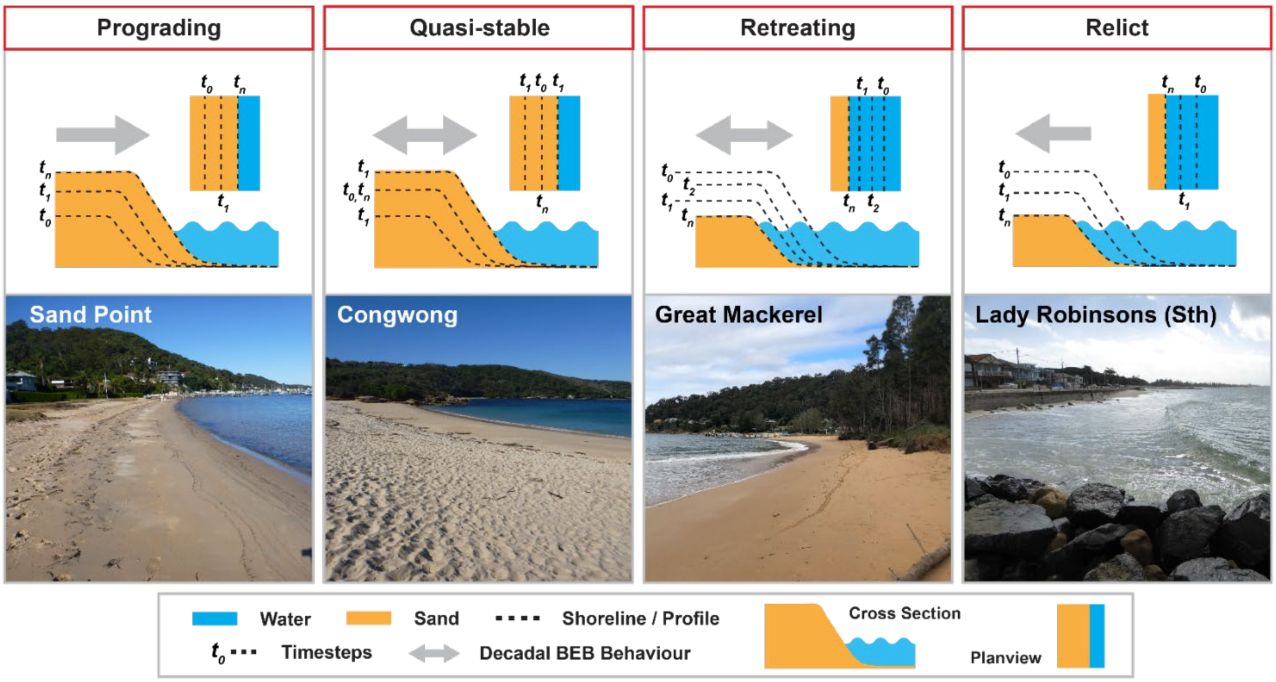


***Figure 10**: A decadal behavioural typology for BEBs. Prograding, Quasi-stable, retreating, and Relict. Behaviours are shown with an example BEB from Pittwater and Kamay.*

A key finding is that BEB shoreline recovery is slower than open-coast beaches, which is typically within 3 years following extreme storms in this region (Harley et al., 2016). If we note that recovery time $t_r = E_s/A_r$ where $E_s$ is amount eroded during storm and $A_r$ is the rate of accretion between storms, then the requirement for *quasi-stable* beaches is $t_{st} > E_s/A_r$. Thus beaches may start to retreat due to increased storm frequency (smaller $t_{st}$), more severe erosion during storms (larger $E_s$), or slower accretion between storms (smaller $A_r$). In some areas, climate change may alter storm frequency, wave height and incident direction, which change $E_s$. Moreover, local anthropogenic changes like dredging and structures can alter wave propagation into estuaries/bays, changing both $E_s$ and $A_r$; structures can alter $E_s$ and $A_r$ while nourishment can increase $A_r$. More recognition of the influence of anthropogenic impacts alongside the slow-evolution paradigm for BEBs has major implications for the management of estuary and bay shorelines in major cities.

***Table 3:*** *Decadal behavioural typology of the BEBs in Pittwater and Kamay.*

| | BEB Location | Behaviour | Behaviour after intervention |
|---|---|---|---|
| **Pittwater** | Great Mackerel | *Retreating* (north/south)<br>*Quasi-stable* (central) | *Retreating* (north/south)<br>*Quasi-stable* (central) |
| | Station | *Quasi-stable* (north)<br>*Prograding* (south) | - |
| | Snapperman | *Retreating* (north)<br>*Quasi-stable* (central/south) | - |
| | Sand Point | *Quasi-stable* (north)<br>*Prograding* (south) | - |
| **Kamay** | Yarra Bay | *Relict* (north)<br>*Quasi-stable* (south) | *Quasi-stable* (all) |
| | Currewol | *Relict* (north)<br>*Quasi-stable* (south) | *Quasi-stable* (all) |
| | Congwong | *Quasi-stable* | - |
| | Little Congwong | *Quasi-stable* | - |
| | Lady Robinsons | *Quasi-stable* (north)<br>*Relict* (central)<br>*Relict* (south) | *Prograding* (north)<br>*Quasi-stable* (central)<br>*Retreating* (south) |

## 5.2. Geomorphological influences on decadal BEB evolution

### *5.2.1. Distance from estuary or bay entrance*

Distance from the estuary/bay entrance controls BEB responses to and recovery from storms (Fig. 7b; Fig. 9c). BEBs that are close to the entrance present behaviours that are commonly *quasi-stable* (e.g., Congwong and Station); in contrast with *prograding*, *retreating* and *relict* behaviours away from the entrance (Fig. 10; Table 3). Costas et al. (2005), Eulie et al. (2017) and Gallop et al. (2020) suggest that exposure to swells and a continuing supply of marine sediment are essential to maintain BEB shorelines (Fig. 7b; Fig. 9c). For instance, Kamay has ~10 times the number of storms that with waves that enter the estuary compared to Pittwater (Fig. 5). In Kamay, following the 1974 storms, BEBs located near an entrance exhibited rapid recovery, e.g., Congwong close to the entrance recovered in 3 years and was *quasi-stable* compared to Lady Robinsons south which is 6 x further from the entrance and had only partial recovery after 15 years and was *retreating/relict*. (Fig. 9c, g; Table 3). Alternatively, BEBs that have *prograding* behaviours (e.g., Sand Point) may be at the inner limit of swell propagation where waves no longer have energy required to transport marine sediments (Fig. 6d; Fig. 8d; Fig. 10); suggesting that *prograding* BEBs are controlled by tidal, wind-wave or other processes. For example, Austin et al. (2018) and Vila-Concejo et al. (2020) found that wave energy within estuaries can be refracted/diffracted around headlands, along estuary/bay shores and over tidal shoals and deltas, encouraging alongshore transport on BEBs. Overall, we suggest that entrance-adjacent BEBs may be less vulnerable to decadal management issues and more attention may be required for those with less stable behaviours.

#### *5.2.2. Flood-tide deltas*

A flood-tide delta may act as a source or sink for BEB sediments (Austin et al., 2018; Vila-Concejo et al., 2011). For example, Great Mackerel had a sediment sink (*retreating*) while Snapperman had a sediment source (*quasi-stable*) (Fig. 7a, c). Both of these BEBs are adjacent to the Pittwater flood-tide delta but have different behaviours (Table 3) and exposure to swells (Gallop et al., 2020). Harris et al. (2020) and Vila-Concejo et al. (2007) indicate that BEB sediments can be transported by storm waves onto flood-tide deltas and sandy tidal shoals, with this transport becoming permanent if sediments are moved below the modal wave base (Austin et al., 2018) or removed by subsequent tidal action. Gallop et al. (2020) outline the *retreating* behaviour at Great Mackerel (Table 3), suggesting that sediments eroded from the shoreface post-storm may be transported alongshore or form a subtidal terrace that extends to flood-tide deltas and may be a one-way process where sediment is transported over the delta-front into deeper water. These authors and others (Costas et al., 2005; Jackson, 1995; Nordstrom and Jackson, 2012) state that the limited wave energy under modal conditions can fail to return all eroded BEB sediments. Alternatively, sediments may arrive onto BEBs from nearshore sources (Vila-Concejo et al., 2010; Vila-Concejo et al., 2007) or have travelled along estuary/bay shores from the entrance (Harris et al., 2020). This is evident whereby sediments transported along the eastern estuarine shore between Station and Snapperman (both *quasi-stable*), with the latter adjacent to the flood-tide delta (Fig. 1g; Table 3). Meanwhile, similar shoreline decadal shoreline erosion is evident at other sites near flood-tide delta in Port Stephens in SE Australia (Austin et al., 2018; Harris et al., 2020) as well as adjacent to tidal shoals and tidal channels on back-barrier BEBs in Portugal (Carrasco et al., 2012). We suggest source and sink pathways associated with flood-tide delta must be considered in BEB management.

#### *5.2.3. River and creek mouths*

BEBs in drowned river valleys (e.g., Pittwater) commonly have river or creek mouths that drain through BEBs into the main estuary channel (Roy et al., 2001). BEBs adjacent to river or creek mouths are highly dynamic as they are at the intersection of fluvial and marine processes (Vila-Concejo et al., 2020). These BEBs present a range of decadal shoreline behaviours from *prograding* (e.g., Lady Robinsons north) through to *retreating* (e.g., Great Mackerel) (Fig. 7a; Fig. 9e; Table 3). At Great Mackerel the decadal *retreating* behaviour and slow recovery (up to 11 years) following the 1974 storms appears to be impacted by the alongshore migration of the creek mouth which narrows beach widths (Fig. 1c; Fig. 6a; Fig. 10). Meanwhile, Gallop et al. (2020) and Cowell (1989) point out that short-term BEB morphodynamics are equally impacted by river or creek mouths, when BEBs lose more sand due to river and creek outputs. Equally, BEBs located in low-lying settings (e.g., Kamay) on the front of sand spits and prograded barriers (e.g., Lady Robinsons south) can represent *retreating* or *relict* behaviours due to fluvial processes (Fig. 10). These BEBs can require anthropogenic intervention to stabilise or mitigate BEB shorelines (Fig. 2; Fig. 8g), especially if shorelines are modified (e.g., Lady Robinsons south). Alternatively, BEBs can accrete downdrift if alongshore sediment transport is the primary shoreline mechanism (Nordstrom and Jackson, 2012). At Lady Robinsons north we suggest alongshore transport, the northern river mouth and a retaining wall encourages the decadal *prograding* behaviour (Fig. 2; Fig. 8d). Meanwhile, the variability of the dynamic southern section could be attributed to the proximity to the Tucoerah River which may supply sediment to prominent nearshore tidal shoals (see Fig. 8f). To understand BEB shorelines near river and creek mouths we must consider that they are naturally variable and are dynamic BEB shorelines due to interaction of fluvial, tidal and wave forcing.

### 5.3. Importance of anthropogenic interventions for BEBs

BEBs in the same estuary often have different decadal shoreline behaviours (Fig. 10). BEBs with the largest shoreline change are typically those with a history of anthropogenic intervention, for example Currewol and Yarra bay were *relict* and post-intervention are *quasi-stable* (Table 3). While at Lady Robinsons, reductions in beach width are likely due to a sediment sink that developed following dredging in the 1970s and 1990s for the Sydney Airport runways and the port navigation channel (Fig. 2; Fig. 9e–g). Increases to estuary and bay water depth due to dredging, can destabilise shorelines by modifying waves processes and redirecting swell energy to BEB shorelines and by creating sediment sinks (Austin et al., 2018; Nordstrom, 1992); this supports our *retreating* behaviour along central and south Lady Robinsons (Table 3). In the Algarve (Portugal), Carrasco et al. (2012) notes that dredging of nearshore tidal shoals and channels is the primary control for BEB shoreline retreat, even at locations not exposed to swell waves. We suggest these factors contribute to *retreating* and *relict* shoreline behaviours with important management implications.

Anthropogenic interventions to counter decadal shoreline retreat in estuaries and bays include groynes and revetments (Nordstrom and Jackson, 2012). This study and others (Frost, 2011; Lowe and Kennedy, 2016) emphasise how groynes and sand nourishment can mitigate the effects of repetitive storm erosion, alongshore sediment transport, shoreline rotation and increased wave exposure on BEB shorelines (Fig. 8a–b). For instance, at Lady Robinsons there are two examples of groyne construction following bay dredging (Fig. 2; Table 3). Yarra Bay and Currewol both display *relict* shorelines with a clockwise shoreline rotation following the construction of the Port Botany revetment in the early 1970s and erosion from the 1974 storms. This highlights how interventions change sediment supply or exposure for adjacent BEBs (Fig. 2; Fig. 9a–b, e–g; Fig. 10). Nordstrom (1992) and Qiao et al. (2018) emphasise how BEBs are vulnerable to anthropogenic interventions, with decadal losses to BEB widths in Hong Kong and in the USA. We propose that swell energy diverts, refracts and reflects on to the previously sheltered shorelines evident at Yarra Bay and Currewol, which now both have a central groyne structure and *quasi-stable* behaviours (Table 3). Furthermore, anthropogenic interventions to river and creek mouths can cause *retreating* (Great Mackerel) and *prograding* (Lady Robinsons north) behaviours (Fig. 2; Table 2), as shorelines readjust over decadal scales. Historically, engineering interventions rarely considered BEB shorelines which in many cases (e.g., Lady Robinsons, Yarra Bay) require subsequent intervention (groynes, sand nourishment) to maintain the shorelines (Fig. 2; Table 3). Future anthropogenic interventions must consider decadal BEB behaviours, to preclude future shoreline retreat.

## 6. CONCLUSIONS

We quantify and compare the decadal-scale behaviours of sandy shorelines in natural and heavily modified estuaries. Through an assessment of 76 years of imagery (1941–2017), we propose a behavioural typology of BEB decadal evolution including: *prograding*, *quasi-stable*, *retreating* and r*elict* shorelines. *Prograding* BEBs have shorelines that migrate seaward, *quasi-stable* BEBs present minimal decadal change, *retreating* and *relict* BEBs have shorelines that migrate landward with partial or no recovery between storms, respectively. BEBs near the entrance of estuaries and bays are typically swell exposed and *quasi-stable*. They recover at rates comparable to open coast beaches (< 3 years). In contrast, BEBs farther from the entrance exhibit all four behaviours, are less swell exposed and when they recover do so at slower rates (< 15 years) – that commonly exceed storm return timescales. *Prograding* BEBs are typically away from the entrance, swell sheltered and controlled by other processes including fluvial/tidal alongshore transport. BEBs adjacent to a flood-tide delta can present *quasi-stable* and *retreating* behaviours depending on if the delta acts as a sediment source or sink and this impacts recovery (< 3 and < 11 years respectively). Decadal behaviours are the most variable on BEBs adjacent to river and creek mouths due to the interaction of fluvial and marine processes, alongshore transport and anthropogenic intervention (e.g., groynes and revetment, sand nourishment, dredging). Dredging and land reclamation can lead to *retreating* and *relict* shorelines if new sediment sinks are created and if wave energy is redirected through dredged channels to previously protected BEBs. Meanwhile, groynes and sand nourishment are measures that can be successful in creating *quasi-stable* BEB, if interventions consider the altered wave or sediment conditions within a modified estuary or bay.

## 7. ACKNOWLEDGEMENTS

We acknowledge the traditional custodians of the Aboriginal lands on which this research was conducted. Thanks to the NSW Department of Planning, Industry and Environment (DPIE) and the Newcastle Region Library for supplying historical aerial images, to Manly Hydraulics Laboratory (DPIE) for supplying wave data, and to David M. Kennedy from the University of Melbourne for Pittwater NearMap images. AVC and JLL are grateful for support received through the Partnership Collaboration Award linking the University of Sydney with University of California Davis.

## 8. DATA AVAILABILITY

The datasets reported in the paper are available from the corresponding author on reasonable request.

## 9. REFERENCES

Aijaz, S., Treloar, D., 2003. Beach management options at Lady Robinsons Beach, Botany Bay, Australia, Oceans 2003. Celebrating the Past ... Teaming Toward the Future (IEEE Cat. No.03CH37492), pp. 238-245 Vol.231.

Austin, T., Vila-Concejo, A., Short, A., Ranasinghe, R., 2018. A Multi-Scale Conceptual Model of Flood-Tide Delta Morphodynamics in Micro-Tidal Estuaries. Geosciences, 8(9), 324.

Australian Bureau of Meteorology, 2015. Stormy Weather: A century of storms, fire, flood and drough in New South Wales, Australian Government.

Birkemeier, W.A., Nicholls, R.J., Lee, G.-h., 1999. Storms, storm groups and nearshore morphologic change, Coastal Sediments. ASCE, pp. 1109-1122.

Boak, E.H., Turner, I.L., 2005. Shoreline Definition and Detection: A Review. Journal of Coastal Research, 688-703.

Bryant, E.A., Kidd, R., 1975. Beach erosion, May-June, 1974, Central and South Coast, NSW.

Carrasco, A.R., Ferreira, Ó., Matias, A., Freire, P., 2012. Natural and human-induced coastal dynamics at a back-barrier beach. Geomorphology, 159-160, 30-36.

Costas, S., Alejo, I., Vila-Concejo, A., Nombela, M.A., 2005. Persistence of storm-induced morphology on a modal low-energy beach: A case study from NW-Iberian Peninsula. Marine Geology, 224(1–4), 43-56.

Cowell, P.J., 1989. Advisory Report on Management of Beach Erosion at Mackerel Beach. Coastal Protection Advisory Service.

Cowell, P.J., Kannane, A., 2000. Review of Changes to the Shores and Bed of Botany Bay: Past and Future.

Cowell, P.J., Nelson, H., 1991. Management of beach erosion due to low swell, inlet and greenhouse effects: Case study with computer modelling, 10th

Australasian Conference on Coastal and Ocean Engineering, Hamilton, New Zealand, pp. 311-315.
Davies, P.R.E., McIlquham, J.D., 2011. Geotechnical design for the Port Botany expansion project, Sydney. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, 164(3), 149-167.
Eulie, D.O., Walsh, J.P., Corbett, D.R., Mulligan, R.P., 2017. Temporal and Spatial Dynamics of Estuarine Shoreline Change in the Albemarle-Pamlico Estuarine System, North Carolina, USA. Estuaries and Coasts, 40(3), 741-757.
Foster, D.N., Gordon, A., Lawson, N., 1975. The Storms of May-June 1974, Sydney, NSW, Second Australian Conference on Coastal and Ocean Engineering, 1975: The Engineer, the Coast and the Ocean, The. Institution of Engineers, Australia, pp. 1.
Frost, G., 2011. Review of Coastal Processes and Evaluation of the Impact of the Constructed Groynes along Lady Robinsons Beach, Botany Bay, New South Wales, Australia. Bachelor of Environmental Science (Honours) https://ro.uow.edu.au/thsci/17, University of Wollongong, Wollongong, Australia.
Gallop, S.L., Vila-Concejo, A., Fellowes, T.E., Harley, M.D., Rahbani, M., Largier, J.L., 2020. Wave direction shift triggered severe erosion of beaches in estuaries and bays with limited post-storm recovery. Earth Surface Processes and Landforms, 45(15), 3854-3868.
Harley, M.D., 2017. Coastal Storm Detection. In: P. Ciavola, G. Coco (Eds.), Coastal Storms: Processes and Impacts. Wiley, Chichester, pp. 1-19.
Harley, M.D., Turner, I.L., Kinsela, M.A., Middleton, J.H., Mumford, P.J., Splinter, K.D., Phillips, M.S., Simmons, J.A., Hanslow, D.J., Short, A.D., 2017. Extreme coastal erosion enhanced by anomalous extratropical storm wave direction. Scientific Reports, 7(1), 6033.
Harley, M.D., Turner, I.L., Splinter, K.D., Phillips, M.S., Simmons, J.A., 2016. Beach response to Australian East Coast Lows: A comparison between the 2007 and 2015 events, Narrabeen-Collaroy Beach. Journal of Coastal Research, 388-392.
Harris, D.L., Vila-Concejo, A., Austin, T., Benavente, J., 2020. Multi-scale morphodynamics of an estuarine beach adjacent to a flood-tide delta: Assessing decadal scale erosion. Estuarine, Coastal and Shelf Science, 106759.
Jackson, N.L., 1995. Wind and Waves: Influence of Local and Non-local Waves on Mesoscale Beach Behavior in Estuarine Environments. Annals of the Association of American Geographers, 85(1), 21-37.
Jones, G., 1981. Effects of dredging and reclamation on the sediments of Botany Bay. Australian Journal of Marine and Freshwater Research, 32, 369-377.
Kennedy, D.M., 2002. Estuarine Beach Morphology in Microtidal Middle Harbour, Sydney. Australian Geographical Studies, 40(2), 231-240.
Komar, P.D., 1998. Beach Processes and Sedimentation. Prentice Hall.
Kulmar, M., Gordon, A., 1987. Coastal Processes of the Pittwater North Western Foreshores, Eighth Australasian Conference on Coastal and Ocean Engineering, 1987: Preprints of Papers. Institution of Engineers, Australia, pp. 109.
Lowe, M.K., Kennedy, D.M., 2016. Stability of artificial beaches in Port Phillip Bay, Victoria, Australia. Journal of Coastal Research, 75(sp1), 253-257, 255.

Nordstrom, K.F., 1992. Estuarine Beaches: An introduction to the physical and human factors affecting use and management of beaches in estuaries, lagoons, bays and fjords. Springer Netherlands.

Nordstrom, K.F., Jackson, N.L., 2012. Physical processes and landforms on beaches in short fetch environments in estuaries, small lakes and reservoirs: A review. Earth-Science Reviews, 111(1), 232-247.

Novak, K., 1992. Rectification of digital imagery. Photogrammetric engineering and remote sensing, 58, 339-339.

OEH, 2018. Estuaries of NSW. Office of Environment and Heritage.

Qiao, G., Mi, H., Wang, W., Tong, X., Li, Z., Li, T., Liu, S., Hong, Y., 2018. 55-year (1960–2015) spatiotemporal shoreline change analysis using historical DISP and Landsat time series data in Shanghai. International Journal of Applied Earth Observation and Geoinformation, 68, 238-251.

Rocchini, D., Metz, M., Frigeri, A., Delucchi, L., Marcantonio, M., Neteler, M., 2012. Robust rectification of aerial photographs in an open source environment. Computers & Geosciences, 39, 145-151.

Roy, P.S., Williams, R.J., Jones, A.R., Yassini, I., Gibbs, P.J., Coates, B., West, R.J., Scanes, P.R., Hudson, J.P., Nichol, S., 2001. Structure and Function of South-east Australian Estuaries. Estuarine, Coastal and Shelf Science, 53(3), 351-384.

Ruggiero, P., Kaminsky, G.M., Gelfenbaum, G., 2003. Linking proxy-based and datum-based shorelines on a high-energy coastline: implications for shoreline change analyses. Journal of Coastal Research, 57-82.

Shand, T., Goodwin, I., Mole, M., Carley, J., Browning, S., Coghlan, I., Harley, M., Preston, W., 2010. NSW coastal inundation hazard study: coastal storms and extreme waves.

Short, A., Trenaman, N., 1992. Wave climate of the Sydney region, an energetic and highly variable ocean wave regime. Marine and Freshwater Research, 43(4), 765-791.

Short, A.D., 1993. Beaches of the New South Wales Coast; a guide to their nature, characteristics, surf and safety. Sydney University Press, Sydney.

Vila-Concejo, A., Austin, T.P., Harris, D.L., Hughes, M.G., Short, A.D., Ranasinghe, R., 2011. Estuarine beach evolution in relation to a flood-tide delta. Journal of Coastal Research, 190-194.

Vila-Concejo, A., Gallop, S.L., Largier, J.L., 2020. Sandy beaches in estuaries and bays. In: D.W.T. Jackson, A.D. Short (Eds.), Sandy Beach Morphodynamics. Elsevier, London.

Vila-Concejo, A., Hughes, M.G., Short, A.D., Ranasinghe, R., 2010. Estuarine shoreline processes in a dynamic low-energy system. Ocean Dynamics, 60(2), 285-298.

Vila-Concejo, A., Short, A., Hughes, M., Ranasinghe, R., 2007. Flood-tide delta morphodynamics and management implications, Port Stephens, Australia. Journal of Coastal Research, 50, 705-709.

Wilson, K.M., Power, H.E., 2018a. Seamless bathymetry and topography dataset for Botany at 10m gridsize. PANGAEA.

Wilson, K.M., Power, H.E., 2018b. Seamless bathymetry and topography dataset for Hawkesbury River at 50m gridsize. PANGAEA.

Wilson, K.M., Power, H.E., 2018c. Seamless bathymetry and topography dataset for Sydney Harbour (Port Jackson) at 10m gridsize. PANGAEA.