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Stability of artificial beaches in Port Phillip Bay, Victoria, Australia.

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ABSTRACT

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This study investigates the drivers of beach morphodynamics on the highly modified fetch-limited beaches of the urbanised north-eastern coast of Port Phillip Bay in south-eastern Australia. Repetitive beach profiling, sediment characterization, and aerial photo analysis were conducted to quantify morphodynamic change across six distinct beach systems on a seasonal to annual-decadal scale. The observed morphologies contained features similar to those found on open-ocean wave-dominated and tide-dominated beaches, and included reflective unbarred beaches and intermediate beaches with low-tide terraces or transverse bar-rip systems. Sediment typically ranged from medium to coarse or very coarse in size. The consistency of wave energy across the study sites suggests that sediment size is the primary determinant of beach morphodynamic state, and the relatively low energy of Port Phillip Bay suggests that only storm conditions are energetic enough to mobilise sediment and alter beach morphology. On a seasonal scale, alongshore sediment transport is a major driver of beach change, and groynes and other coastal modifications have considerable influence on planform beach morphology. Over the medium term it appears that these beaches are eroding towards a landward position of equilibrium. With current projections of sea level rise it is expected that rates of beach erosion and sediment loss will accelerate over the coming decades, leading to an increased necessity for beach renourishment or other management interventions if wide beach profiles are to be maintained.

ADDITIONAL INDEX WORDS: *Estuarine beaches, morphodynamics, beach renourishment.*

INTRODUCTION

Beaches that form on fetch-limited estuarine coastlines are markedly different to those found on the open coast. They tend to be smaller and narrower, often sediment starved, and strongly influenced by littoral drift processes (Nordstrom, 1992, Jackson *et al*., 2002, Kennedy, 2002). Morphodynamics on fetch-limited estuarine beaches differ from open-ocean systems as they lack consistent energy input of long period swell waves (Masselink and Pattiaratchi, 2001). Their morphodynamics are instead strongly influenced by spatial and temporal differences in fetch and therefore wave energy, irregular bathymetry, sediment source, and topographic constraints.

Increasing population density and development on many estuarine coastlines have resulted in a high degree of coastal modification and disruption to natural processes. However, despite the importance of estuarine beaches for coastal protection, industry, and recreation, their morphodynamics remain poorly understood when compared to open-ocean systems. As a result, many millions of dollars are spent each year managing urban estuarine beaches, often with little regard to their long-term evolution.

While it is widely accepted that the dominant open-ocean morphodynamic models, such as those of Wright and Short (1984) and Masselink and Short (1993), have limited applicability to estuarine beaches (Jackson *et al*., 2002, Nordstrom and Jackson, 2012), applying the results of previous estuarine studies across multiple estuarine systems is also difficult. The substantial differences in boundary conditions, both between and within different estuaries, do not easily support extrapolation to different environments. In addition, the relative frequency of coastal management works, when compared to long-term coastal evolution, can make it difficult to differentiate natural trends from the observed variation of estuarine beaches.

This study investigates the beach morphodynamics of the north-eastern coastline of Port Phillip Bay, Victoria, Australia, in the context of both its unique estuarine boundary conditions and substantial anthropogenic modification; the city of Melbourne is located along this coastline. This study seeks to identify the dominant processes driving short to medium term geomorphic change through repetitive beach profiles, sediment characterisation, and aerial photo analysis. It then compares these estuarine processes with current beach morphodynamic models, and proposes a conceptual model for considering the effects of variable energy inputs into estuarine systems.

Background

Port Phillip Bay is situated in the south-east of Australia and covers an area of approximately 1,950 km2 (Figure 1). The Bay has a total coastline length of 260 km, a maximum depth of 24 m, and is connected to the open ocean through a narrow channel to the south (Bird, 1993). All incoming ocean swell is refracted

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through the channel and dissipates over shallow sand banks and mud islands in the far south, leaving the majority of beaches exposed exclusively to wind waves. Port Phillip Bay is considered a strong wind bay and has a distinctly seasonal wind climate, with predominant west and southwesterlies during summer, and north and northwesterlies during winter (Goodfellow and Stephenson, 2005). Tidal range is small and reduces from 1.1 m in the south to 0.6 m in the north.

Port Phillip Bay has a long history of coastal modification, including the construction of seawalls and groynes. A substantial number of beaches have also been renourished since the 1960s, though the success of these works has varied (Black and Rosenberg, 1992).

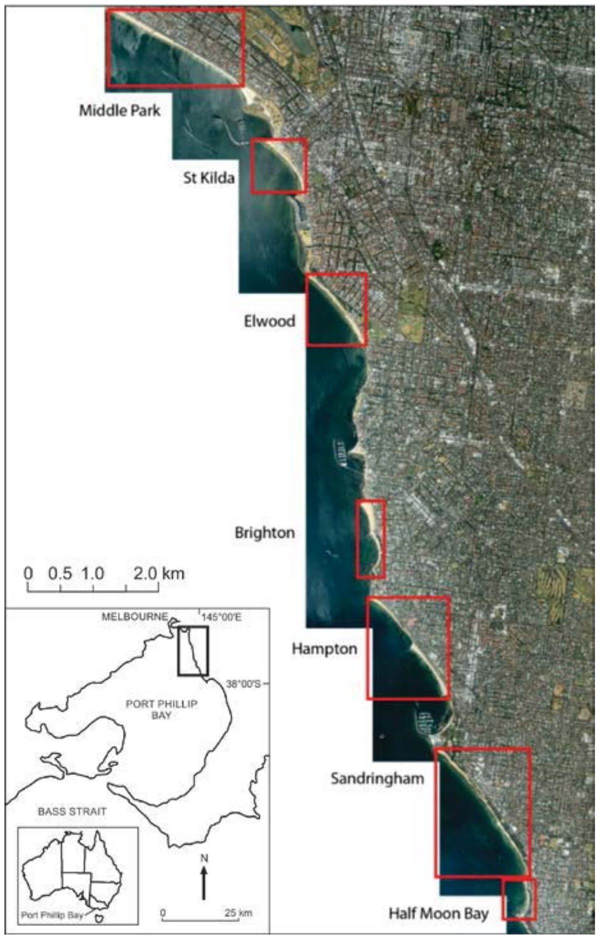

Figure 1. Location of the study area within Port Phillip Bay, Victoria, Australia. The red boxes show the individual beach systems studied.

For this study, a subset of six Port Phillip Bay beaches were chosen for analysis: Middle Park, St Kilda, Elwood, Brighton, Hampton, and Sandringham, including Half Moon Bay (Figure 1). All are located in the northeast of Port Phillip Bay and provide contrasting geological and anthropogenic settings, while still being exposed to similar wind and wave climates. Beach renourishments conducted within the study area between 1997 and 2012 are outlined in Table 1.

Table 1. *Beach renourishments on the north-eastern coastline of Port Phillip Bay between 1997 and 2012 (Department of Sustainability and Environment, 2012).*

Location	Year	Volume (m^3)	Completed beach width	Sediment source	Grain size (D50)	Length
Hampton, southern end	1997	100,000	50 m	Dredge, offshore	0.9 mm	1,000 m
Sandringham, between groynes	2009	40,000	40 m	Dredge, offshore	0.9 mm	330 m
Middle Park, eastern end	2009	80,000	60 m	Dredge, offshore	0.5 mm	700 m
Elwood	2011	36,000	35 m	Quarry sand	1.1 mm	800 m

METHODS

All study sites were surveyed repeatedly between March and August 2012. An initial set of 51 beach transects was recorded, after which 23 transects were surveyed an additional one to three times. All surveys were conducted within two hours of low tide, from a fixed point at the back of the beach to approximately 0.8 m below mean sea level (MSL). Sediment samples from all sites were collected and analysed using a Laser Particle Sizer. Historic shorelines mapped from five sets of aerial photographs taken between 2001 and 2011 were analysed using the Digital Shoreline Analysis System (DSAS version 4.3) extension for ArcMap (Thieler *et al*., 2009).

RESULTS

Considerable morphological and sedimentological variation was observed across the study site and during the study period. Results from Middle Park Beach and Sandringham Beach are presented here in most detail as they present contrasting geological settings and variation in the types and degrees of coastal modification.

Middle Park Beach is backed by seawall and high-density development. Vegetated dunes are present at its western end. At the time of surveying, beach width, as measured from the seawall to mean sea level (MSL), decreased from up to 71.9 m in the west to 23.6 m in the east, while the subtidal gradient was gentle ($1.76 \pm 0.81°$). The subaqueous morphology was characterised by a series of shore-attached transverse bars which shifted throughout the study period (Figure 2a).

Sandringham Beach, in contrast, is backed by cliffs and vegetated bluffs, and the centre of the beach is dominated by two large rock groynes. Sandringham Beach varied considerably in width both across the site (43.5 m at the northern end to 9.5 m in the south) and across the survey period (the maximum change observed was from 12.2 m in March to 22.8 m in August). The most variation was observed either side of the groynes; profiles north of the groynes accreted during the study period (Figure 2b), while those to the south eroded. Despite these variations, beachface width and slope remained relatively constant. Subaqueous sand bars were absent from most profiles, and were only observed between the two groynes and at Half Moon Bay.

Of the remaining study sites, Elwood and Hampton Beaches were geomorphically similar to Sandringham, and demonstrated considerable seasonal variation, particularly around groynes where beach width varied by up to 4.1 m. In contrast, a distinct low tide terrace feature was observed at St Kilda Beach, varying in width. Brighton Beach remained relatively stable throughout the study period.

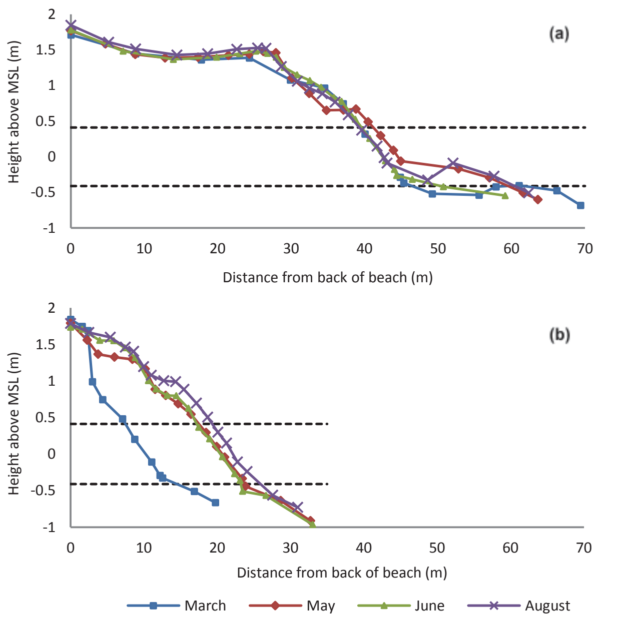

Figure 2. Beach profile variation from March 2012 to August 2012 at (a) Middle Park and (b) Sandringham. Dotted lines indicate the mean high water spring (MHWS) and mean low water spring (MLWS) tide levels.

The beaches within the study area also exhibited cross-shore and alongshore variability in sediment character. In general, sediment was found to be finest at the bar, coarsest at the lower swash limit, then progressively finer towards the back of the beach. There was a clear distinction between the coarse to very coarse sand beaches, including Elwood, Hampton, Brighton, and Sandringham Beach, and the medium sand beaches (Middle Park, St Kilda, and Half Moon Bay). Mean beachface sediment size of the former ranged between 985 and 1,198 µm, while the latter ranged between 427 and 639 µm. Statistical analysis found that sediment at Sandringham Beach was significantly coarser than at Middle Park Beach in all sample locations except the bar (Figure 3).

Analysis of aerial photography found that there has been considerable variation in beach width and shoreline orientation since 2001. The influence of beach renourishment (Figure 4a) and groyne construction (Figure 4b) were evident. Furthermore, analysis of the rate of change statistics found the majority of beaches in the study area are eroding over the medium term (Table 2). The sections of beach that have not been recently renourished eroded at an average rate of 0.3 m per year from 2001 to 2011, a statistically significant trend ($t_{calc} = 6.03$, $t_{0.05(2)222} = 1.97$). Only the northern section of Brighton Beach experienced net accretion since 2001 without the addition of sediment. Renourished beaches have seen large volumes of sediment reworked offshore, though the rate at which this occurred has varied: in the two years following renourishments in 2009, the average rate of erosion in affected areas was 2.0 m per year at Sandringham and 3.8 m per year at Middle Park.

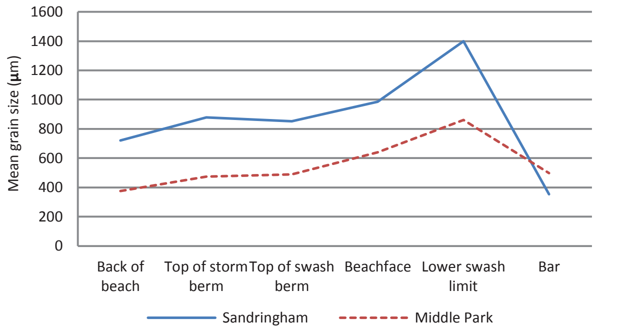

Figure 3. Variation in mean sediment size, based on the average of all samples analysed at Sandringham (n = 8) and Middle Park (n = 6).

Figure 4. (a) Shoreline change at Middle Park between 2001 and 2011, showing shoreline accretion due to renourishment in 2009 (green line), followed by subsequent erosion (pink line). (b) Shoreline orientation at Sandringham as influenced by the construction of the northern groyne in 2006; the blue and red lines show the pre-groyne shoreline orientation. This area was also renourished in 2009.

Table 2. *Average magnitude of shoreline changes across the study sites.*

Site	Number of aerial transects	2001 width (m)	2011 width (m)	Δ 2001-2004 (m)	Δ 2004-2007 (m)	Δ 2007-2009 (m)	Δ 2009-2011 (m)	Net shoreline movement from 2001 to 2011 (m)	% change between 2001 and 2011 shorelines
Middle Park	46	43.1	42.0	-4.5	+1.8	+3.7	-2.1	-1.1	3%
St Kilda	18	31.1	29.2	-2.5	-1.8	+2.3	0.0	-1.9	-6%
Elwood	29	24.5	30.9	-5.3	-0.8	+2.4	+10.2	+6.4	26%
Brighton	29	50.5	51.6	+0.8	-0.2	+0.7	-0.3	+1.1	2%
Hampton	40	43.1	34.4	-6.9	+0.1	-0.8	-1.1	-8.7	-20%
Sandringham	57	23.7	19.4	-7.7	+1.3	+5.0	-2.9	-4.3	-18%
Half Moon Bay	9	18.7	14.5	-6.5	+2.4	+1.9	-1.9	-4.2	-22%

DISCUSSION

Based on the observed spatial and temporal variation in beach morphology and sedimentology, it is evident that the beaches of the north-eastern coastline of Port Phillip Bay are both highly dynamic and influenced by varying boundary conditions, including sediment, topography, and the degree of anthropogenic influence.

A number of observed features, in particular subaqueous bar configurations, are similar to those found on open-ocean beaches; however, Port Phillip Bay is clearly not an open-ocean system. Temporal variation in wave energy inputs, and as such relative tidal range, on estuarine beaches makes it difficult to classify these systems under traditional process-driven models that assume relatively consistent energy input.

Fetch-limited environments rely on local winds to generate waves. When there is little or no wave energy input into the system, beaches remain inactive. Changes to beach morphology occur when there is sufficient input of wave energy to surpass a threshold of sediment movement, overcoming the inertia of the grains and bringing them into motion (Komar, 1976). This threshold is dependent on grain size, density, and shape.

Once sufficient energy is available to mobilise sediment, it is apparent that the process dominance of an estuarine beach can change rapidly. Where wave heights are low compared to tidal range, tidal processes predominate, and macro to mesotidal-type morphologies are expected to develop. Subsequently, when wave energy increases such that waves overtake tides as the predominant morphodynamic process, microtidal-type morphologies may be observed.

Figure 5 proposes a conceptual model of the thresholds at which the varying morphodynamic processes come into dominance on estuarine beaches. Unlike the threshold for sediment movement, the threshold between tide-dominated and wave-dominated processes is assumed to be independent of sediment size, and is represented by a horizontal line. As wave energy increases further, thresholds between various microtidal morphologies may be surpassed; these transitions are influenced by sediment size, as outlined in Wright and Short (1984).

It is suggested that the beaches in Port Phillip Bay oscillate between periods of low wave energy when they are geomorphically stable, and stormy periods when wave energy is sufficient to drive the development of bars and other features. The dominance of storms as the primary driver of beach morphodynamics in Port Phillip Bay is further supported by the fact that the dimensionless fall velocities calculated for the beaches in the study area under modal conditions are considerably lower than those typically associated with the observed morphological features (Table 3).

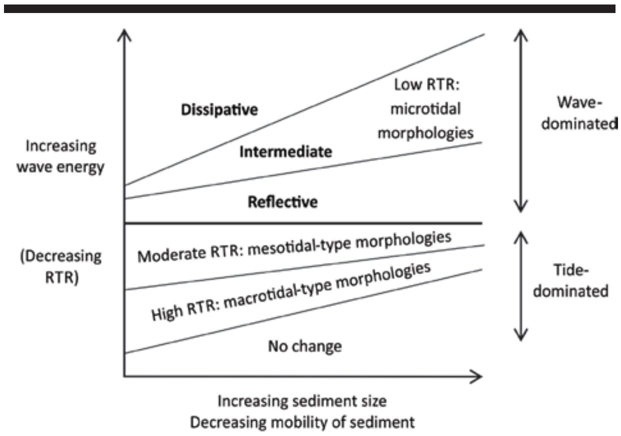

Figure 5. Conceptual estuarine beach model: thresholds for macro, meso and microtidal-type beach morphologies. The variation in relative tidal range (RTR) is also outlined.

Table 3. *Calculated dimensionless fall velocity values (Ω) for the beaches in the study area, compared to those for analogous open-ocean beach states.*

Site	Calculated Ω	Analogous open-ocean beach state	Ω and RTR for relevant open-ocean models
Middle Park	0.27 to 0.54	Intermediate Transverse bar-rip.	Ω ≈ 3 to ≈ 2, RTR: micro
St Kilda	1.14	Intermediate Low-tide terrace	Ω ≈ 3 RTR: meso
Elwood	0.11 to 0.19	Reflective	Ω < 1 RTR: micro
Brighton	0.20 to 0.51	Reflective to low-tide terrace	Ω < 1, Ω ≈ 2 RTR: micro
Hampton	0.08 to 0.13	Reflective	Ω < 1 RTR: micro
Sandringham	0.08 to 0.37	Reflective	Ω < 1, Ω ≈ 2 RTR: micro
Half Moon Bay	0.35	Intermediate Transverse bar-rip	Ω ≈ 3 RTR: micro

As wave energy is approximately equal across the study sites, sediment size is considered the primary determinant of beach morphology. This conceptual model can therefore be applied to the study sites in Port Phillip Bay.

Sandringham, Hampton, Brighton, and Elwood beaches are composed of coarse sand, are stable during calm periods, and are reworked as wave-dominated reflective beaches during high energy events.

The finer grained beaches of Middle Park and Half Moon Bay more easily surpass the threshold between reflective and intermediate states, and are reworked into low tide terrace and transverse bar and rip morphologies during high energy events.

St Kilda Beach, though it has the finest sediment, does not adopt the highest energy beach state during storm conditions. However, this beach also arguably receives the least wave energy of all the study sites, as it is sheltered by a marina, pier, and groyne. As such, it is suggested that wave energy at St Kilda Beach may not exceed the threshold between mesotidal and macrotidal morphologies, and instead the beach adopts a lower energy mesotidal low tide terrace morphology.

While storms may be the primary drivers of overall beach morphology in Port Phillip Bay, longshore sediment transport arguably has the greatest impact on seasonal variability. Beach planforms rotate in response to oblique wave approach in order to reduce the angle of wave attack (Jackson and Cooper, 2010). In Port Phillip Bay, seasonal changes to the prevailing wind direction alter the theoretical short-term planform position of equilibrium, where incident wave angle is parallel to the shoreline. The rate of change is greatest immediately following the shift in prevailing winds (March to May; see Figure 2b), and decreases over time. The effects of longshore sediment transport are exacerbated by the presence of groynes or other structures, which disrupt some alongshore movement. On beaches less affected by longshore sediment transport, subaerial erosion and accretion is concentrated at the beachface (see Figure 2a); this is consistent with Nordstrom's (1992) estuarine erosion models.

As outlined earlier, those beaches that have not been recently renourished have been eroding since at least 2001. While beach widths will continue to oscillate in response to seasonal changes, this erosional trend suggests that the long-term equilibrium position for Port Phillip Bay beaches is landward and upward of their current position. Based on the tendency of these beaches to erode towards a landward position of equilibrium, it is highly likely that they will continue to need periodic renourishment in order to maintain wide profiles. Furthermore, with current projections of sea level rise, it is expected that rates of beach erosion will accelerate over the coming decades. This would lead to an increased necessity for beach renourishment or other management interventions if wide beach profiles are to be maintained.

CONCLUSIONS

Port Phillip Bay, a unique and highly modified estuarine system, exhibits distinct patterns of beach morphodynamics and beach change over the short and medium terms. Even within a relatively small section of the Bay, variation in boundary conditions, specifically sedimentology and the degree of coastal modification, have significant impacts on beach morphology.

Unlike on open-ocean beaches, it was found that only periodic storm events are energetic enough to rework large subaqueous bar features, and thus control the morphodynamic state of beaches in Port Phillip Bay. Low wave energy during calm periods is insufficient to significantly alter beach morphology. Furthermore, longshore sediment transport is a significant driver of beach change, though seasonal fluctuations in prevailing winds limits its impact over the longer term.

A comprehensive understanding of estuarine beach dynamics should be used to inform coastal management planning and decision making. The coastal managers of Port Phillip Bay, and the managers of many other estuarine beach systems, will likely have to contend with accelerating rates of beach erosion over the coming decades (Walsh *et al*., 2004, Bird, 2006). While beach renourishment is currently a method of choice for shoreline maintenance in highly developed areas, it is possible that the associated costs may one day outweigh the benefits, in which case alternative methods of shoreline management may need to be adopted.

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