Marine Geology 355 (2014) 173–188

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Lagrangian observations of circulation on an embayed beach with headland rip currents

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ARTICLE INFO

Article history:
Received 18 February 2014
Received in revised form 26 May 2014
Accepted 30 May 2014
Available online 6 June 2014

Keywords:
Drifters
Pocket
Intermediate
Topographic
Surfzone exit rate
Exchange
Morphology

ABSTRACT

This study describes the first comprehensive measurements of nearshore current patterns across the entire extent of an embayed beach bounded by headland rip currents. A field experiment at Whale Beach, NSW, Australia provides valuable insights into: (i) embayment-wide spatial and temporal flow behaviour; (ii) rates of cross- and alongshore water exchange; and (iii) the influence of geological control by headlands on morphology and circulation. Lagrangian flow data was obtained using 34 GPS drifters with 293 individual deployments, over a single ebbing tidal cycle during moderate-low energy ($H_s = 1$ m) oblique wave forcing. In-situ wave and current data, and bathymetric data were also collected. Beach morphology was dominated by a large mid-beach rip channel with lesser headland rip channels. Mean flow rates were 0.6 ms^{-1} in the mid-beach channel and 0.4 ms^{-1} in the headland channels, with the majority of cross-shore water volume flux (~60%) through the central channel. A weak alongshore current O (0.1 ms^{-1}) was forced by the oblique offshore wave angle. Rip current velocities, flow variability, and rate of surfzone exits by Lagrangian drifters increased as water level decreased. Transient currents on a planar bar along the northern half of the beach, with velocity standard deviation up to 0.2 ms^{-1}, were not tidally modulated. Lagrangian time series were used to differentiate four current regimes (rip cell, rip head, planar bar and offshore low energy zone) based on mean velocity, velocity variability and degree of tidal modulation. An increase in surfzone exit rates by drifters was observed from south (upwave) to north (downwave), with exit rates per drifter deployment of 22% at the south headland rip, 65% at the mid-beach open rip, and 80% at the north headland rip. The high rate of drifter exits contrasts previous observations on open coast beaches. Observed flow behaviours are attributed to wave shadowing at the upwave (protected) end of the beach, and longshore currents forced by oblique waves deflected offshore at the downwave headland. These field observations are in good agreement with recent numerical modelling. A relationship between bathymetric variability and current intensity was determined, with cross-shore average mean velocity correlating with a parameterisation of bathymetric alongshore non-uniformity. This study demonstrates that flow behaviour and exchange rates can vary along the length of an embayed beach due to geological control. This research has implications for transport of organisms, nutrients and pollutants, is relevant to beach safety practitioners, and can be used in calibration of numerical models.

1. Introduction

Embayed beaches occur on rocky coastlines worldwide, including the sandstone dominated Sydney region, NSW, Australia. The primary difference between embayed and open coast beaches is the control exerted by geology, where hard topography (headlands) refracts, diffracts and attenuates offshore waves (Short and Masselink, 1999; Castelle and Coco, 2012). On the NSW coastline, these effects reduce modal offshore significant wave height (H_{s0}) from 1.6 m to a breaking wave height (H_b) of 1.1 m (Short, 2010). Geological control can limit sediment supply, impacting on beach state (Jackson et al., 2005; Loureiro et al., 2012b; Loureiro et al., 2013), with most beaches in the Sydney region occurring in compartmentalised cells with dynamic equilibrium within the embayment, but little to no sediment by-passing of headlands (Short, 2010).

The degree of headland control on an embayed beach can be characterised into three embayed beach states (Short and Masselink, 1999; Castelle and Coco, 2012): (i) *cellular* circulation — occurring with high waves and/or a short beach, under strong geological control, where one rip (mid-beach) or two rip channels (at headlands) drain the beach; (ii) *intermediate* circulation — moderate geological control, with wider rip channel spacing and headland rip currents; and (iii) *normal* circulation — low waves and/or a long beach, with no geological

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http://dx.doi.org/10.1016/j.margeo.2014.05.020
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control away from the vicinity of headlands, and many open beach rips occurring that behave hydrodynamically as per open coast rips. The revised embaymentisation parameter δ' of Castelle and Coco (2012), is determined as the number of surfzone widths (X_s) that fit within the embayment length (L). With $\delta' \leq 9$ indicating cellular circulation, and $\delta' \geq 16$ indicating normal circulation.

$$\delta' = \frac{L}{X_s} \quad (1)$$

A special case of *cellular* circulation occurs under high wave forcing (H_b >3 m), where *mega-rips* are generated, flowing multiple surfzone widths offshore (Short, 2007), and generating severe erosion (Loureiro et al., 2012a).

Hydrodynamic studies of open beach circulation have received significant attention in recent years, including Eulerian observations (e.g. MacMahan et al., 2005; Bruneau et al., 2009), Lagrangian observations (e.g. MacMahan et al., 2010), video observations (e.g. Turner et al., 2007), radar observations (Haller et al., 2014), physical models (e.g. Haller et al., 2002) and numerical modelling (e.g. Reniers, 2009; Castelle et al., 2013). Studies conducted (or simulated) on embayed beaches, have focussed attention away from the headlands, or have been conducted on long embayed beaches (>2 km), under *normal* circulation (Short and Masselink, 1999), limiting or neglecting the potential impacts of geological control (Brander, 1999; Ranasinghe et al., 2004; Reniers et al., 2004; Holman et al., 2006; Ribas et al., 2007; Austin et al., 2010; Castelle et al., 2010).

As such, examination of the geologically controlled hydrodynamics of embayed beaches, and headland rip currents in particular, have not been effectively measured directly, with studies limited to video observations (Ojeda and Guillén, 2008; Enjalbert et al., 2011; Gallop et al., 2011), topographic surveys (Loureiro et al., 2012a), numerical modelling (Silva et al., 2010; Castelle and Coco, 2012, 2013), and rudimentary or limited direct observations (Talbot and Bate, 1987; Huntley et al., 1988; McCarroll et al., 2014).

An area of recent interest has been rates of cross-shore exchange due to rip currents in various morphological settings, with implications for sediment transport (Loureiro et al., 2012a,b), biological processes (Talbot and Bate, 1987; Shanks et al., 2010), and beach safety (Brander and MacMahan, 2011; Miloshis and Stephenson, 2011; McCarroll et al., 2014). Rates of cross-shore exchange can be estimated from the proportion of Lagrangian drifters that are transported by currents from within the surfzone to beyond the extent of breaking waves, either per deployment per hour (MacMahan et al., 2010), per rip entry (Scott et al., 2014), or by the exchange rates of simulated drifting particles in numerical models (Reniers et al., 2009). Observed exchange rates have been found to average ~20% of drifters exiting the surfzone per hour on an open-coast micro-tidal beach (MacMahan et al., 2010), and to vary significantly (0 to 70% exits per rip entry) on a macro-tidal beach, depending on wave and tide conditions (Scott et al., 2014). Cross-shore exchange rates in headland rip currents, and in open beach rip cells affected by nearby headlands, are yet to be tested with field observations.

Recent numerical simulation to explore cross-shore flux on embayed beaches (Castelle and Coco, 2012, 2013), found higher rates of exchange than observations of open beaches, determining that wave direction was an important control on headland rip behaviour. For beaches of 0.5 km–1 km in length, the upwave headland exhibited dominant rotational behaviour (low exchange), while the downwave headland was a concentrated offshore jet (high exchange). The upwave case is physically similar to eddies in the lee of groynes resulting from wave shadowing (Gourlay, 1974; Pattiaratchi et al., 2009), and the downwave case is analogous to the wave exposed side of groynes deflecting longshore currents offshore (Wind and Vreugdenhil, 1986). While the phenomena of upwave/downwave differences in headland rips under oblique forcing have been qualitatively observed in the case of mega-rips (Loureiro et al., 2012a), no quantitative field measurements exist under normal hydrodynamic conditions across an embayment.

In order to improve our understanding of nearshore currents and associated circulation in embayed beaches, this study describes embayment-wide Lagrangian drifter observations across a 600 m long intermediate embayed beach, where current types observed included: (i) open beach bathymetrically controlled rip currents (MacMahan et al., 2006, 2010; Austin et al., 2010; Dalrymple et al., 2011); (ii) headland topographically controlled rip currents (Short, 2010; Loureiro et al., 2012a; Castelle and Coco, 2013); (iii) alongshore currents forced by oblique waves (Komar and Inman, 1970; Longuet-Higgins, 1970; Orzech et al., 2010); (iv) transient currents on near planar topography resulting from hydrodynamic interaction (Johnson and Pattiaratchi, 2004); and (v) nearshore currents resulting from cross-shore exchange with the surfzone (MacMahan et al., 2010).

The aims of the study are to: (i) determine how circulation systems are distributed and integrated across an intermediate embayed beach; (ii) identify spatial and temporal variability in flow behaviour; and (iii) determine rates of exchange for rip channels in an embayed beach environment, and relate this to geological controls and wave forcing. To our knowledge, this is the first study to comprehensively measure the nearshore wave and current field across the entire extent of an embayed surfzone.

2. Study location

The study was conducted at Whale Beach, 30 km north of Sydney, NSW, Australia (Fig. 1a). The beach is 600 m long (Fig. 1b–c), bounded by sandstone and shale headlands, with the southern end facing east, and the northern end facing ESE, with greater exposure to the prevailing south-easterly moderate-high energy wave climate (Short and Trenaman, 1992). Modal H_s is 1.5 m (Short and Trenaman, 1992), and peak period (T_p) is 10 s (SLSA, 2009). Sediment is medium grained and tides are microtidal (<2 m range). A time-merged rectified image taken around mid-tide, observed from a video camera on the northern headland (Fig. 1c), is overlaid on the bathymetry (Fig. 1b). Surfzone width (Fig. 1b) and wave angle within the embayment were estimated from the video imagery.

3. Methods

3.1. Field observations

Bathymetric surveys were conducted on Oct 3, 2012 using a RTK-GPS and echosounder equipped personal water craft (PWC). Surveys of the sub-aerial beach and intertidal zone were conducted using a survey grade GPS mounted in a backpack on a human walker. Survey lines were spaced at 10 m from the sub-aerial beach out to the ~− 6 m contour, with 20 m spacing beyond that in the outer embayment. Important features such as rip channels and headlands had additional closely spaced (<5 m) survey lines. Survey data were interpolated to a 4 m square grid with a cubic algorithm, and smoothed over a 20 m span in the cross- and alongshore with a weighted (1-cos^2) function. Total station surveys were used for headlands, with the outer headlands determined from marine charts.

Hydrodynamic data was collected on Oct 4, 2012. Offshore wave data were obtained from the Sydney directional wave buoy situated ~14 km south of the field site in 80 m depth (Manly Hydraulics Lab, 2012). Local wave data were recorded by two pressure transducers (PT) beyond the surfzone in ~4 m depth, and from an irregular alongshore array within the surfzone (Fig. 1b, P1–4 and PUV1–3). P1–P4 were Aquistar PTX, situated near bed-level, sampling at 8 Hz (P1,3,4) or 3 Hz (P2). Eulerian current data were obtained from three Sontek Hydra Acoustic Doppler Velocimeters (ADV), located in each rip channel (Fig. 1b, PUV1–3). The ADV's recorded velocity 0.6 m above the bed, with co-located PT near bed level, with all data sampled at 5 Hz.