THE ROLE OF 2DH CIRCULATION IN SAND BAR MIGRATION MODELS

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Abstract

A new, nonlinear equation for sand bar migration has been developed to study sand bar response to changing wave forcing. The bar system is represented by two parameters: the alongshore mean bar position (*x(t)*) and the amount of 2DH bar morphology present (*a(t)*). Cross-shore bar migration is driven by a physics-based sediment transport formulation, with the assumption that variations in the roller contribution to the undertow (and therefore the presence of wave breaking), along with the presence of 2DH morphology (assumed to cause horizontal circulation) are the two main contributors. The model was tested using video images from Palm Beach, NSW, Australia. Seven data sets, totalling 562 days and 11 major storms over a four-year period were used. The model was capable of reproducing sand bar migration over a variety of wave conditions with the presence of 2DH variability found to increase onshore migration rates during moderate wave conditions, a role that has often been assumed negligible.

Introduction

The nearshore region is considered to be highly variable at a range of spatial and temporal scales, with sand bars being a particularly visible signature of this phenomenon (Keulegan 1948; Plant et al. 1999; Ruessink et al. 2003). Observations have shown that both response times and time-varying equilibrium bar positions are dependent on wave height (e.g. (Wright and Short 1984; Plant et al. 1999; Plant et al. 2001). Offshore migration in response to storms is found to be rapid, while the response to intervening calm periods, corresponding to onshore migration, is found to be much slower.

The majority of models that aim to describe the cross-shore migration of sand bars assume that any alongshore variability present in the morphology has a negligible effect on the fluid and sediment transport dynamics, such that the system can be represented by one horizontal dimension (1DH). A series of process-based models related to sand bar migration have been proposed in the literature (e.g. (Gallagher et al. 1998; Drake and Calantoni 2001; Hoefel and Elgar 2003; Henderson et al. 2004)). Many are based on an energetics approach (e.g. (Bagnold 1963; Bowen 1980; Bailard 1981)) and assume that cross-shore processes, such as undertow and velocity skewness, dominate the forcing terms. While most of these models are able to reproduce offshore sand bar migrations, they have shown varying degrees of success at reproducing onshore migration rates such that our understanding of the physics is not considered solved. One particular issue may be their sensitivity to input errors such as the evolving cross-shore profile and the cross-shore distribution of sediment and wave characteristics. Alternatively, parametric models offer a simplified approach. These models assume that morphology and forcing parameters can be represented using a discrete set of parameters, such as sand bar position, *x(t),* reducing the complexity and sensitivity of the model. Model equations are generally behavioural and represent a few processes assumed to dominate both the forcing and the response (e.g. (King and Williams 1949; Greenwood and Davidson-Arnott 1979; Roelvink and Stive 1989; Plant et al. 1999; Marino-Tapia et al. 2007)). Despite their success at highlighting some of the key parameters driving sand bar migration (e.g (Plant et al. 1999)), the direct link to physical processes is unclear.

While efforts continue into improving 1DH models, it is hard to neglect the fact that 2DH morphology is quite common (Zenkovich 1967; Sonu 1973; Wright and Short 1984; Lippmann and Holman 1990) and may indeed play a significant role in sand bar migration. Wright and Short (1984) and Wright et al. (1985) observed that alongshore bar trough systems were associated with energetic conditions, described by a dimensionless fall velocity (Dean 1973) value greater than 4.7. The existence of such conditions is short lived, with mean residence times of roughly 2-5 days (Lippmann and Holman 1990; Ranasinghe et al. 2004), suggesting the 1DH assumption may have limited validity during non-energetic conditions. In fact, the two most commonly occurring beach states are the Transverse Bar Rip (TBR) and the Rhythmic Bar and Beach (RBB), accounting for 70-80% of the temporal variation (Wright et al. 1987; Lippmann and Holman 1990; Ranasinghe et al. 2004). Additionally, under non-storm conditions (down-state transitions) changes in morphology are found to be more dependent on the prior state rather than on the wave forcing, suggesting a positive feedback system. In light of these observations, Plant et al. (2006) proposed a parametric model to describe sand bar migration that explicitly included terms based on the bar sinuosity, $a(t)$, the alongshore standard deviation of bar position for all alongshore length scales from 200 to 1000 m. By modeling the dynamics of both $x(t)$ and $a(t)$ simultaneously as a function of wave forcing, $F(t)$, represented by the offshore root mean square (rms) wave height squared, $H_o^2(t)$, Plant et al. (2006) were able to explicitly explore the contribution of 2DH morphology to sand bar migration and system stability.

In this paper we test a newly developed equation (Splinter 2009) for sand bar migration rates to further explore the role of 2DH variability on onshore sand bar migration rates. Unlike previous parametric models (Plant et al. 1999; 2006), the equation is derived from principles of sediment transport and then reduced to a parametric form through the conservation of mass equation (Splinter et al. submitted). The non-linear form requires sediment transport to go to zero as forcing becomes negligible, an additional improvement over Plant et al. (2006).

Field Data

Field Site Description

Palm Beach, NSW was chosen as the study site due to its highly dynamic nature and the existence of an Argus camera system that provided near continuous images of wave breaking patterns. Palm Beach is a 2 km-long, east facing, open ocean embayment, located approximately 30 km north of Sydney, Australia (Figure 1). The beach extents are defined by 2 headlands; Barrenjoey to the north and Little Head to the south. The nearshore beach slope is 0.03 (Wright et al. 1980) and the median grain size is 0.30 mm (Wright et al. 1980). The location is micro-tidal and swell-dominated, with no significant seasonal variability in the wave conditions (Short and Trenaman 1992). The dominant wave direction is from the SSE with the occasional E and NE swell and wave heights averaging 1.5 m, but can reach 3 - 6 m during storm conditions (Short and Trenaman 1992).

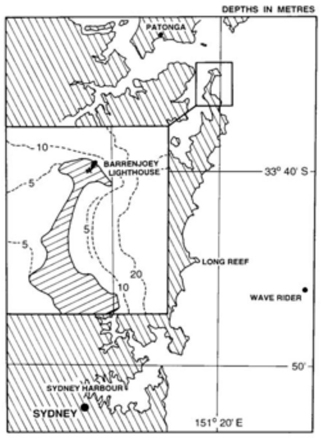

Figure 1. Map of Palm Beach, NSW.

Wave Characterization

Offshore wave conditions (significant wave height, H_s, wave angle, θ, and significant wave period, T_s) were obtained from a directional wave rider buoy located at Long Reef, 20 km south of Palm Beach, in a depth of 80 m (Figure 1). Daily wave conditions at the 10 m contour were calculated using the 2D HISWA wave refraction model (Holthuijsen et al. 1989). Breaking wave heights, H_b, were defined following Komar (1974) setting the breaking parameter, γ, to 0.42 (Thornton and Guza 1982). Similarly, local wave heights at the bar location, H_{bar}, were calculated using linear wave theory and conservation of energy flux (e.g. (Dean and Dalrymple 1991)). Wave heights defined at the location of the bar were set to the minimum of the local wave height, H_{bar}, the breaking wave height, H_b, or *0.5h*.

Fraction of Breaking (b)

The fraction of wave breaking (utilized in the roller contribution in the undertow term) depends on the non-dimensional wave height, parameterized using a sigmoid curve (Splinter et al. submitted):

$$b = \frac{1}{1 + e^{\frac{-\gamma_b - \gamma_o}{\Gamma}}}. \quad (1)$$

The mixed variable, $\gamma_b = H_b / h_{bar}$, relates the wave height at one location (the break point) to the depth at another location (the bar crest). The values of $\gamma_o = 0.39$ and $\Gamma = 0.055$ were chosen to best fit wave breaking data from Duck94 (hourly statistics for October 11-12,1994) and NSTS (November 1978) (Thornton and Guza 1983). Tidal variation, Δ_t, affects the percent of breaking (Alexander and Holman 2004) over the course of a day due to water depth variation over the bar. Since we use daily images of wave breaking, tidal variation is included in (1) through an adjusted Γ_t:

$$\Gamma_t = \Gamma\left[1 + \gamma_b \frac{\Delta_t}{h}\right]. \quad (2)$$

Beach Characterization

Video Data

A two-camera Argus video-imaging station (Holman et al. 1993; Aarninkhof and Holman 1999; Holman et al. 2003) was installed in the Barranjoey lighthouse in January, 1996. The cameras are located 115 m above mean sea level and face south towards Palm Beach. Only the wide-angle lens camera, C1, is used as it provides a view of 90% of the study area. During camera installation, the location of the camera and several visible ground control points (GCPs) were surveyed relative to a known benchmark. Calibration of the camera pointing parameters were computed based on the image locations of these GCPs (Holland et al. 1997).

Images were rectified to an overhead (plan) view using standard photogrammetric transformations. The curved shoreline was transformed to a straightened co-ordinate system following the method and values of Alexander and Holman (2004). Shoreline position, $x_s(y',t)$, was defined following the method of Alexander and Holman (2004) and then filtered using a spatial 25-pt Hanning window to remove any short scale features or anomalous data.

Daytimex images (daily average of all 10-min time exposure images collected during daylight hours) were used to estimate mean bar position, *x(t),* and 2DH variability, *a(t)*. Bar positions, $x_b(y',t)$, were estimated at 5 m intervals in the alongshore direction based on preferential wave breaking patterns (Lippmann and Holman 1989; van Enckevort and Ruessink 2001; Alexander and Holman 2004). Mean sand bar position, *x(t)*, was defined as the alongshore-averaged distance between the measured sand bar position, $x_b(y',t)$ and the shoreline, $x_s(y',t)$.

The surf zone variability index, *a(t)*, is a proxy for 2DH currents, which in turn are a function of both the bathymetry (where waves are breaking) and the incoming wave field (the intensity of breaking). Daytimex images were first detrended to account for lighting variations in the images due to grazing angle (Splinter 2009). The location of active wave breaking over the bar/morphology was defined by landward, $x_-(y',t)$, and seaward, $x_+(y',t)$, limits based on first exceedances of intensity above a threshold of 0.8 times the maximum intensity at the defined bar location, $x_b(y',t)$. The Longshore breaking Intensity Profile, $LIP(y',t)$, was found by cross-shore integration of intensities between the landward and shoreward limits of active wave breaking. A composite Longshore Bar Breaking Profile, $LBBT(y',t)$, combining bar position and breaking intensity information was defined as:

$$LBBP(y',t) = x(t) - x_b(y',t) + LIP(y',t)\,. \qquad (3)$$

The surf zone variability index, *a(t)*, was calculated once per day based on $LBBT(y',t)$ using the spectral method described in Plant et al. (2006), within the band 30 m < L_y < 400 m.

Model

The equation for sand bar migration is built from the energetics-based sediment transport theory (Bagnold 1963; Bowen 1980; Bailard 1981)(referred to as BBB herein) and then transformed to a parametric representation using conservation of mass

(Bagnold 1941; Plant et al. 2001; Splinter et al. submitted). The equation is developed in 1DH, looking at deviations about an equilibrium balance associated with changes in the roller contribution. Extensions to 2DH are based on observations and assumptions about the role of circulation cells in net cross-shore transport.

1DH Sediment Transport

We parameterize cross-shore sediment transport, Q_{x_o}, using the formulation similar to Bowen (1980) and Bailard (1981). We assume that onshore and offshore transport terms balance under some wave conditions, γ_{eq}, based on a time-dependent form of non-dimensional wave height, $\gamma_b = H_b / h_{bar}$. We model the residual transport as deviations away from these conditions. We neglect the contribution due to bedload (Gallagher et al. 1998) and due to gravity ($\tan\beta$) since $\tan\beta$ is zero at the sand bar crest. We assume that variations in wave breaking, and thus the roller contribution of the undertow term (Svendsen 1984) is the main contributor to variations in onshore and offshore transport. The final form of our equation is

$$Q_{x_o} = \hat{Q}_{x_o} \left(\gamma_b - \gamma_{eq} \right), \qquad (4)$$

where $Q_{x_o} = \frac{9}{80} b K_s \gamma_{bar}^3 h_{bar} \sqrt{g h_{bar}} \Omega$, Ω is the dimensionless fall velocity term (Dean 1973) and K_s is the dimensionless suspended load transport coefficients. A full derivation of (4) can be found in Splinter et al. (submitted).

2DH Sediment Transport

We hypothesize that the presence of horizontal circulation due to alongshore bathymetric variability facilitates net onshore sediment transport under low wave conditions and increases bar stability against offshore sandbar migration under increasing wave conditions such that

$$Q_{x_o, 2D} = \alpha_1 \kappa_a \hat{Q}_{x_o} \left(\gamma_b - \kappa_a \gamma_{eq} \right), \qquad (5)$$

where κ_a represents the influence of 2DH processes on the alongshore-averaged cross-shore bar migration (Splinter 2009; submitted). Finally, cross-shore sand bar migration can be written as

$$\dot{x} = \alpha_1 \kappa_a M \left(\gamma_b - \kappa_a \gamma_{eq} \right) \qquad (6)$$

where *M* represents the link between sediment transport and parametric terms (Splinter et al. submitted).

Results

Seven data sets were chosen based on reset events described in Holman et al. (2006) and varied in length from 1 - 6 months, totalling 562 days. All data sets included at least one major storm and in most cases, also contained several minor storms in which full resets did not occur. The model was calibrated using the April - May 1996 storm event. Sand bar position is well modelled for the entire data record (R^2 = 0.51, rmse = 19.85 m) (Figure 2). Comparing data and model spectra (Figure 3) we see that sand bar position is well modelled for time periods longer than roughly 6 days. The July - December 1996 data set was the longest run tested. The model did surprisingly well, capturing short term variability as well as the longer term trends in bar position given correct input data of wave conditions and 2DH variability (Figure 2).

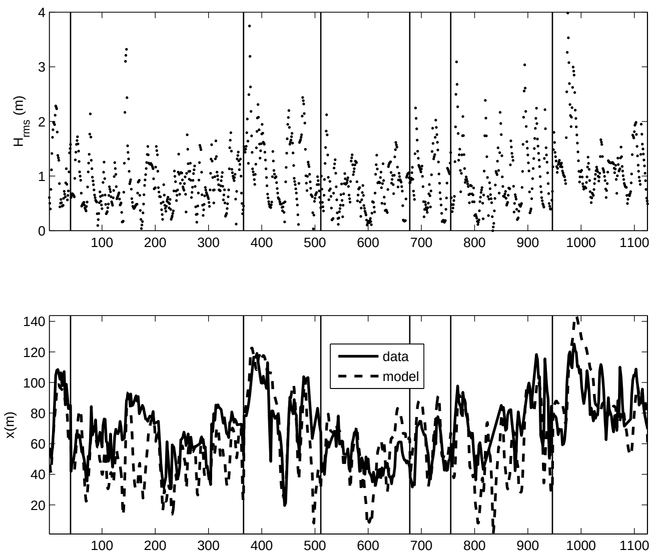

Figure 2. Model - data comparison for entire data record. Individual data sets have been concatenated such that the *x*-axis represents data record number. Vertical lines designate the location where the next data sequence begins.

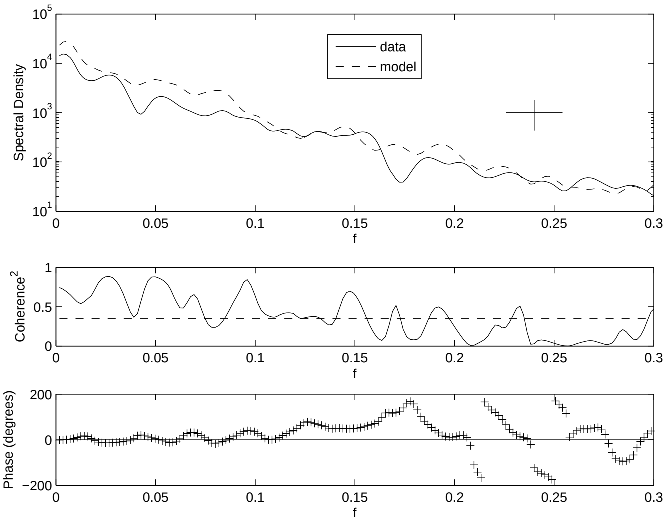

Figure 3. Model-data comparison of bar position spectra. Bar position is well modeled for time scales longer than 6 days.

Discussion

One of the driving forces behind this research was the assumption that despite the overwhelming presence of 2DH morphology, 2DH processes have a negligible influence on cross-shore sand bar migration rates. Using a non-linear model, we tested whether cross-shore sand bar migration rates are influenced by 2DH currents, modelled here as a 2DH surf zone variability factor. We find that onshore migration rates increase under 2DH conditions with respect to a 1DH version of the model

(Figure 4), suggesting for this particular formulation, including the effect of 2DH terms is key. A 1DH version of the model is incapable of reproducing the measured onshore migration, favouring offshore locations and weighted to storm wave conditions (Plant et al. 1999).

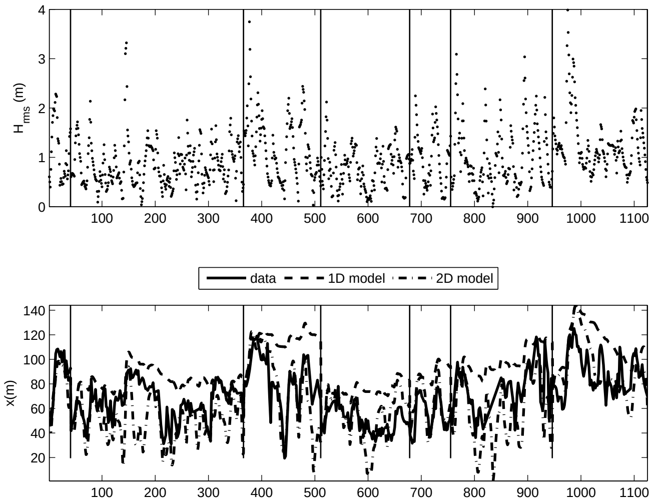

Figure 4. Comparison of 2D model and a 1D equivalent.

Conclusions

A new, nonlinear equation for sand bar migration has been developed to study sand bar response to changing wave forcing. The model contains several improvements over previous works. The parametric form decreases the model sensitivity to input errors, such as cross-shore distribution of wave characteristics or accurate bathymetry profiles and allows the use of remote observations from video images and wave gauges to examine long data records. Despite its parametric form, however, cross-shore bar migration is driven by a physics-based sediment transport formulation under the assumption of constant bar form, modified to allow increasing bar volume with offshore distance. The model also includes the effect of 2DH morphology and the amount of wave breaking present as the main drivers for sediment transport. The model accurately reproduced onshore and offshore sand bar migration rates over a variety of wave conditions. To our knowledge, this is the first model to reasonably predict bar response for multi-storm time scales. Model skill was significant at the 95% level and showed good agreement for time scales longer than 6 days. The presence of 2DH morphology under intermediate breaking conditions was shown to significantly increase the predicted onshore migration rates, agreeing well with observations.

References

Aarninkhof, S. and R. A. Holman (1999). "Monitoring the nearshore with video." Backscatter **10**(2): 8-11.

Alexander, P. S. and R. A. Holman (2004). "Quantitative analysis of nearshore morphological variability based on video imaging." Marine Geology **208**(1): 101-111.

Bagnold, R. A. (1941). The Physics of Blown Sand and Desert Dunes. New York, Methuen.

Bagnold, R. A. (1963). Mechanics of marine sedimentation. The Sea. M. N. Hill. New York, Wiley-Interscience. **3:** 507-528.

Bailard, J. A. (1981). "An energetics total load sediment transport model for a plane sloping beach." Journal of Geophysical Research **86**(C11): 10938-10954.

Bowen, A. J. (1980). Simple models of nearshore sedimentation; beach profiles and longshore bars. The Coastline of Canada. S. B. McCann, Geological Survey of Canada. **Paper 80-10:** 1-11.
Dean, R. G. (1973). Heuristic models of sand transport in the surf zone. Conference on Engineering Dynamics in the Surf Zone, Sydney, N.S.W.
Dean, R. G. and R. A. Dalrymple (1991). Water Wave Mechanics For Engineers and Scientists, World Scientific Publishing Co.
Drake, T. G. and J. Calantoni (2001). "Discrete particle model for sheet flow sediment transport in the nearshore." Journal of Geophysical Research **106**(C9): 19859-19868.
Gallagher, E., R. T. Guza, et al. (1998). "Observations of sand bar evolution on a natural beach." Journal of Geophysical Research **103**(C2): 3203-3215.
Greenwood, B. and R. G. D. Davidson-Arnott (1979). "Sedimentation and equilibrium in wave-formed bars: a review and case studies." Canadian Journal of Earth Sciences **16**: 312-332.
Henderson, S., J. Allen, et al. (2004). "Nearshore sandbar migration predicted by an eddy-diffusive boundary layer model." Journal of Geophysical Research **109**: C06024.
Hoefel, F. and S. Elgar (2003). "Wave-induced sediment transport and sandbar migration." Science **299**(5614): 1885-1887.
Holland, K. T., R. A. Holman, et al. (1997). "Practical use of video imagery in nearshore oceanographic field studies." IEEE Journal of Ocean Engineering **22**(1).
Holman, R. A., A. H. J. Sallenger., et al. (1993). "The application of video image processing to the study of nearshore processes." Oceanography **6**(3): 78-85.
Holman, R. A., J. Stanley, et al. (2003). "Applying Video Sensor Networks to Nearshore Environmental Monitoring." IEEE Pervasive Computing **2**(4): 14-21.
Holman, R. A., G. Symonds, et al. (2006). "Rip spacing and persistence on a pocket beach." Journal of Geophysical Research **111**: C01006.
Holthuijsen, L. H., N. Booij, et al. (1989). "A prediction model for stationary, short-crested waves in shallow water with ambient currents." Coastal Engineering **17**(23): 211-225.
Keulegan, G. H. (1948). An experimental study of submarine sand bars, Beach Erosion Board, U.S. Army Corps of Engineers.
King, C. A. M. and W. W. Williams (1949). "The formation and movement of sand bars by wave action." Geogr. J. **113**: 70-85.
Komar, P. D. (1974). Beach Processes and Sedimentation. Englewood Cliffs, N.J., Prentice-Hall.
Lippmann, T. C. and R. A. Holman (1989). "Quantification of sand bar morphology: A video technique based on wave dissipation." Journal of Geophysical Research **94**(C1): 995-1011.
Lippmann, T. C. and R. A. Holman (1990). "The spatial and temporal variability of sand bar morphology." Journal of Geophysical Research **95**(C7): 11,575-11,590.
Marino-Tapia, I. J., P. E. Russell, et al. (2007). "Cross-shore sediment transport on natural beaches and its relation to sandbar migration patterns: 1. Field observations and derivation of a transport parameterization." Journal of Geophysical Research **112**(C03001).
Plant, N. G., M. H. Freilich, et al. (2001). "The role of morphological feedback in surf zone sand bar response." Journal of Geophysical Research **106**(C1): 973-989.
Plant, N. G., K. T. Holland, et al. (2006). "A dynamical attractor governs beach response to storms." Geophysical Research Letters **33**: L17607.
Plant, N. G., R. A. Holman, et al. (1999). "A simple model for interannual sand bar behavior." Journal of Geophysical Research **104**(C7): 15755-15776.
Ranasinghe, R., G. Symonds, et al. (2004). "Morphodynamics of intermediate beaches: a video imaging and numerical modeling study." Coastal Engineering **51**: 629-655.
Roelvink, J. A. and M. J. F. Stive (1989). "Bar-generating cross-shore flow mechanisms on a beach." Journal of Geophysical Research **94**(C4): 4785-4800.
Ruessink, B. G., K. M. Wijnberg, et al. (2003). "Inter-site comparisons of interannual nearshore bar behavior." Journal of Geophysical Research **108**: doi:10.1029/2002JC001505.
Short, A. D. and N. L. Trenaman (1992). "Wave climate of the Sydney region, and energetic and highly variable ocean wave regime." Australian Journal of Marine and Freshwater Research **43**: 765-791.
Sonu, C. J. (1973). "Three-dimensional beach changes." Journal of Geology **81**: 42-46.
Splinter, K. D. (2009). Development of 2D Models to Estimate Nearshore Bathymetry and Sediment Transport. College of Oceanic and Atmospheric Sciences. Corvallis, Oregon State University. **Doctorate**.

Splinter, K. D., R. Holman, et al. (submitted). "A behavior-oriented dynamic model for sand bar migration and 2DH evolution." Journal of Geophysical Research.
Svendsen, I. A. (1984). "Mass flux and undertow in a surf zone." Coastal Engineering **8**: 347-364.
Thornton, E. B. and R. T. Guza (1982). "Energy saturation and phase speeds measured on a natural beach." Journal of Geophysical Research **87**(C12): 9499-9508.
Thornton, E. B. and R. T. Guza (1983). "Transformation of wave height distribution." Journal of Geophysical Research **88**(C10): 5925-5938.
van Enckevort, I. M. J. and B. G. Ruessink (2001). "Effect of hydrodynamics and bathymetry of video estimates of nearshore sand bar position." Journal of Geophysical Research **106**(C8): 16,969 - 16,979.
Wright, L. D., F. C. Coffey, et al. (1980). Nearshore oceanography and morphodynamics of the broken bay - Palm Beach region, N.S.W. : implications for offshore dredging. Sydney, Australia, Coastal Studies Unit, Department of Geography, The University of Sydney.
Wright, L. D. and A. D. Short (1984). "Morphodynamic variability of surf zones and beaches: A synthesis." Marine Geology **56**: 93-118.
Wright, L. D., A. D. Short, et al. (1987). "The Morphodynamic Effects of Incident Wave Groupiness and Tide Range on an Energetic Beach." Marine Geology **74**: 1-20.
Wright, L. D., A. D. Short, et al. (1985). "Short-term changes in the morphodynamic states of beaches and surf zones: An empirical predictive model." Marine Geology **62**: 339-364.
Zenkovich, V. P. (1967). Processes of Coastal Development. White Plaines, NY, USA, Oliver and Boyd.