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Bar Splitting: Systems Attributes and Sediment Budget Implications for a Net Offshore Migrating Bar System

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ABSTRACT

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Net offshore bar migration or NOM, refers to the systematic seaward migration of longshore (primary) sand-bars across the surf zone. NOM appears to be the product of storm-induced seaward bar migration (sediment transport) exceeding landward bar migration (sediment transport) during intervening fairweather periods. NOM also appears to involve the cross-shore redistribution of sediment rather than the continual loss of sediment to the shoreface. While ‘grain by grain’ return processes appear to predominate within the outer surf zone, alternative return mechanisms may exist within the inner surf zone. The aim of this paper is to assess whether sediment traveling landward within inner bifurcates formed during the process of bar splitting can offset a NOM-induced cross-shore sediment imbalance. Bar splitting has been observed on several NOM coasts and involves a longshore bar bifurcating, with the inner bifurcate detaching, moving landward, and in some cases welding to the foreshore. Analysis of several years of morphological data from Wanganui, on the west coast of New Zealand’s North Island, found that the sediment gained by the foreshore from inner bifurcate welding amounted to approximately half the sediment lost from the foreshore by newly generated sand-bars which subsequently underwent NOM. In addition, during the study, several other types of 3D morphological behaviour were identified which are also capable transporting sediment shoreward across the inner surf zone as a coherent sand body. Landward migrating secondary bars therefore appear to play a significant role in returning sediment to the inter-tidal beach. Finally, a conceptual morphodynamic model of the NOM system at Wanganui is presented which incorporates 3D morphological behaviour in contrast with existing models which are entirely 2D.

ADDITIONAL INDEX WORDS: *Sand-bar, multi-bar coast, bifurcation, surf zone, nearshore, morphodynamic*

INTRODUCTION

Net offshore bar migration (NOM) refers to the systematic seaward migration of coastal subtidal sand-bars across the surf zone; such bars form upon a widened lower foreshore and disappear several years later in the outer surf zone (Ruessink and Kroon, 1994; Shand and Bailey, 1999; Ruessink et al., 2002; Shand et al., 2004). Since the mid 1980s, NOM has been recognised on several storm-dominated, multi-barred coasts: the North Carolina coast (e.g. Birkemeier, 1984; Lippmann et al., 1993), the Dutch coasts (e.g. de Vroeg et al., 1988, Kroon and Hoekstra, 1993), at Wanganui, on the south west coast of the New Zealand North Island (Shand et al., 1999), and at Hasaki Beach on the Japanese Pacific Coast (Kuriyama, 2002). There are also several other locations where published data indicates NOM behaviour may be occurring, but longer records are required for confirmation. For example: Burley Beach, Lake Huron (Houser and Greenwood, 2004); Agate Beach, Oregon (Haxel and Holman, 2004), and Muriwai Beach, near Auckland on the west coast of the New Zealand North Island (ARGUS data analysed by author). NOM has also been described as 'the offshore progression cycle' by Wijnberg (1996) and 'inter-annual cyclic bar behaviour' by Ruessink and Terwindt (2000). An example of NOM behaviour from the Wanganui Coast is depicted in Fig 1 using a sequence of time-lapse photographs.

Sediment dynamics associated with NOM have long puzzled researchers. Central to the issue is the widely accepted notion that bars move seaward under storm-conditions in response to sediment transport driven by bed return flow (undertow). There exists a variety of field evidence to support this mechanism: sediment tracing studies (e.g. Ingle, 1966); sediment structures (e.g. Greenwood and Davidson-Arnott, 1979); and sediment transport and modelling studies (Gallager et al., 1998). If this is indeed the case, then several hundred cubic metres (per metre longshore) of sediment per bar migration cycle would be lost to the shoreface (Shand et al., 1999). However, a sediment budget analysis for the South Holland coast by Wijnberg (1995), found that the volume of sediment from the longshore sediment flux was several times smaller than the amount which would be lost seaward by NOM. Furthermore, this section of coast was

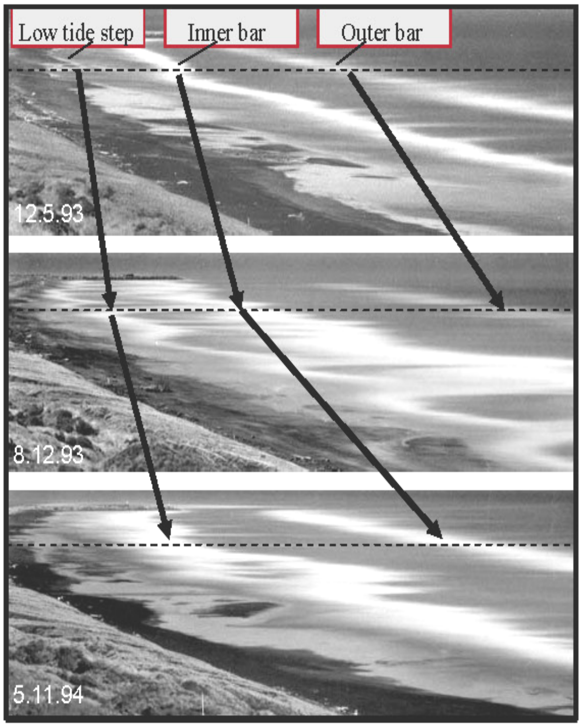

Figure 1. An example of net offshore bar migration along the marked transect (dashed line) using a sequence of 4 minute time-lapse photographs from Wanganui, New Zealand. The high intensity areas result from breaking waves and locate topographic highs such as bar-crests and the low tide step (marked). The outer bar disappeared prior to the last sampling. The inter-sample migration records confirm the arrowed trends, and these data are presented later in Fig 7.

accreting so coastal erosion was not providing a sediment source. Wijnberg (1995, p152) concluded that "…most of the sediment of the degenerating outer bar has to stay within the inshore area..." Sediment transport within a NOM system therefore appears to involve the cross-shore redistribution of sediment, rather than the continual lost of sediment to the shoreface and its replacement from landward or longshore sources.

Landward directed sediment transport occurs in association with sand-bars migrating onshore during lower (fair-weather) wave conditions. Under the influence of landward directed currents associated with asymmetric waves (e.g. Hoefel and Elgar, 2003), and the surface roller effect of broken waves (e.g. Svendsen, 1984), sediment is eroded from the seaward flank of a bar, transported across the bar-crest and then deposited landward of the crest. On 'equilibrium' coasts, this landward sediment transport balances storm-driven seaward transport and, in the longer-term, no net bar displacement in the cross-shore direction takes place, e.g. on single bar, micro-tidal, swell-dominated coasts (Wright and Short, 1984). However, on NOM coasts, such landward sediment transport/bar migration must be insufficient to counteract the storm-induced seaward transport/bar migration.

In the outer surf zone, reduced undertow and an increase in the effectiveness of asymmetric wave-induced sediment transport results in a net landward transport which can lower the seaward bar (Larsen and Kraus, 1992), thereby initiating bar degeneration. Such grain by grain transport, i.e. transport independent of a migrating morphological unit, is thought to redistribute sediment into the landward trough and onto the seaward flank of the adjacent landward bar (Wijnberg, 1995, Ruessink, 1998). Such a mechanism thus helps a bar attain its maximum volume within the mid-outer surf zone (Ruessink and Kroon, 1994).

More recently, Kuriyama (2002) interpreted cross-shore sediment transport rates coupled with an autumn typhoon season and a winter-spring depression season at Hasaki Beach, Japan, as evidence for a grain by grain return process existing across the entire surf zone. However, as at other NOM sites, this onshore sediment transport appears to be associated with the degeneration process of the outer bar which, in the Hasaki case, would be initiated annually during the lower energy summer season separating the two higher energy seasons.

Other studies have shown that significant onshore sediment transport across well developed troughs within the mid-inner surf zone is unlikely (Wright et al., 1986; Houwman and Ruessink, 1996), and Ruessink (1998, p209), comments that some other mechanism is required to move sediment further landward within the inner surf zone.

The possibility of sediment return within some form of landward migrating sand body has been raised by Kuriyama and Lee (2001, p962), who interpreted the second eigenfunction from a complex principal component analysis of Hasaki Beach profile data, as the shoreward migration of an accumulation area. Shand (2000, p173) hypothesized that the return of sediment necessary to balance a NOM-associated deficit, may occur via landward migrating inner bifurcates associated with *bar splitting*.

Bar splitting involves a longshore bar developing a forked (or bifurcated) appearance with the seaward bifurcate migrating further offshore while the inner bifurcate moves into the landward trough and completely detaches from the original bar. In some instances the inner bifurcate subsequently merges with either the adjacent landward bar or the low tide step, causing those features to extend further seaward. The low tide step refers to the step-like feature separating the seaward margin of foreshore from the longshore trough. An example of bar splitting from the Wanganui coast is depicted by the sequence of time-lapse photographs in Fig 2 which have been 'rectified' to correct for perspective distortion.. The mechanism(s) responsible for bar splitting remains a mystery.

The phenomenon of bar splitting has been documented at 2 sites on the west coast of the New Zealand North Island; at Wanganui (Shand and Bailey, 1999), and Muriwai (Donohoe (1998). However, the process appears to be widespread on NOM coasts with the signatures often being evident in published data; for example: on the coast of Holland (Kroon 1990, Fig 5; 1994; Wijnberg and Terwindt 1995, Figs 9-11); at Duck, North Carolina (Holman and Sallenger, 1986, Fig 4; Holman and Lippman,1987, Fig 1), at Nottawasaga Bay, Lake Huron (Bauer and Greenwood, 1990, Fig 17), at Kouchibouguac Bay, Gulf of St Lawrence (Greenwood and Davidson-Arnott, 1975, Fig 6.6), and at Hasaki Beach, Japan (Kuriyama, 2002, Fig 7).

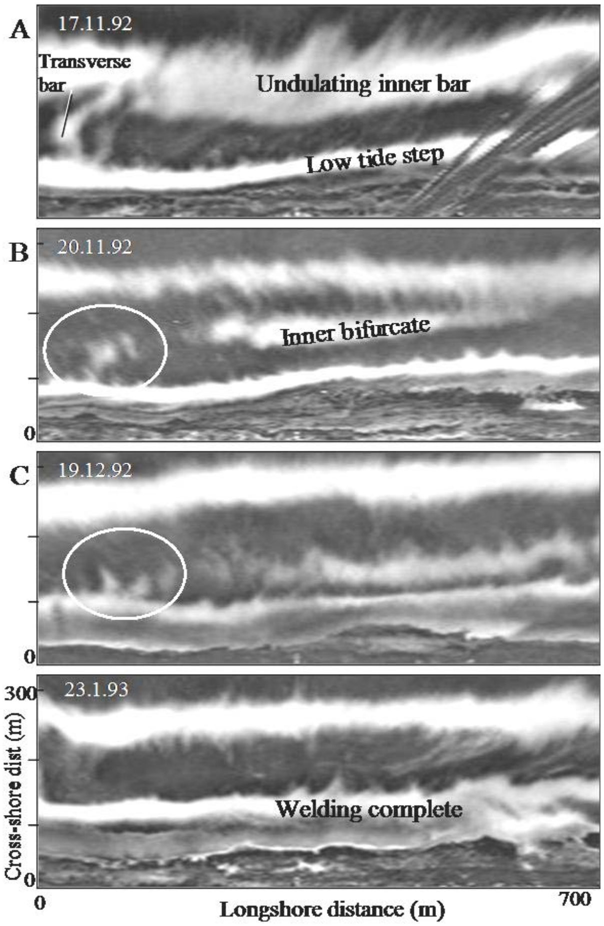

Figure 2 An example of bar splitting using a sequence of 'rectified' (see text) time-lapse photographs from Wanganui, New Zealand.. The form of the inner bar prior to splitting is depicted in A, with B illustrating the recently bifurcated morphology. The inner bifurcate has progressed landward in C, and has welded to the inter-tidal beach in D. This episode of bar splitting was the second observed during the study period. The ellipses in B and C depict a detached transverse bar migrating toward, and welding to, the step (see text).

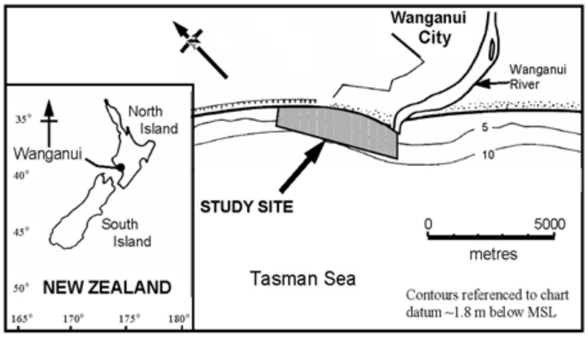

Figure 3. Location map of the Wanganui study site.

It is noted that a variety of terms have been used to denote bar splitting and for the inner and outer bifurcates. Bar splitting was referred to as 'double bar development' by Kroon (1991), while Shand and Bailey (1999) used the term 'bar bifurcation'. However, the term bar splitting is now advocated, as a range of other surf zone processes can result in forked or bifurcated morphologies including bar switching (Shand et al., 2001) and some rip channel-based behaviour noted in Shand (2003). Greenwood and Davidson-Arnott (1975) referred to what appears to be an inner bifurcate as a 'tail', while Holman and Lippmann (1987) used the term 'winged bar'.

This paper is a first semi-quantitative attempt to shed light on whether sediment contained within landward migrating inner bifurcates can offset a NOM-associated sediment imbalance within the inner surf zone. This is achieved by analysing several years of ground survey and image-based data from the Wanganui field site. Finally, the results, together with published information from Wanganui and other NOM coasts, are synthesized into a conceptual morphodynamic model of cross-shore sediment transport for the NOM system.

STUDY SITE

The field site is ~1.5 km from the Wanganui Rivermouth on the southwestern coast of the New Zealand North Island (Fig 3). The nearshore is characterised by fine sand (2 to 3 phi), has a cross-shore slope of ~0.0092 and width of ~530 m. Two subtidal sand-bars are usually present; these bars undergo net offshore migration with the mean life-cycle of a bar being ~3 yrs (Shand et al., 1999). The foreshore is characterised by medium sand (1.7 phi), has an average cross-shore slope of ~0.055 and an average width of ~85 m. About 30% of the time a small amplitude (swash) bar is present on the lower foreshore.

The mean neap tide range is 0.8 m and the mean spring tide range is 2.4 m. The mean deepwater significant wave height is 1.3 m and the 5% excedence value is 2.5 m. The mean wave period is 10.1 s (range 3.5 s to19 s) with sea wave conditions occurring for ~75% of the time and swell waves for the remaining time. Approximately forty two percent of waves approach from the west, ~24% from the south and ~34% lie within one degree of shore-normal. The prevailing WNW wind approaches the coast at ~35 deg from the shoreline, and the wind speed 5% excedence value is 12.4 m/s. The mean value for longshore currents within the inner surf zone is 0.42 m/s and the 5% excedence value is 1.01 m/s. Wave height, wind strength and the magnitude of longshore currents are all positively correlated, as are the direction of these process variables (Shand et al., 2001).

METHODS

To accurately determine sediment volume moving offshore (*Voff*) across the inner surf zone in association with NOM, and moving onshore (*Von*) via inner bifurcates associated with bar splitting, high spatial resolution (cross-shore= 10^0 to 10^1 m, longshore=10^1 m, and elevation=10^{-1}) data of the inter-tidal and subtidal zones are required at 1-5 day intervals. As the logistics of acquiring such data were prohibitive, the following alternative approach was developed which used available image data and morphological maps.

The seaward loss of sediment under NOM, was estimated by the cross-shore change in low tide step location associated with bar generation, while the landward gain in sediment from bar splitting was estimated by the cross-shore change in step location associated with inner bifurcate welding. It is noted that on the Wanganui coast, the low tide step corresponds with a well defined change in slope between the foreshore and the inner trough. These situations are schematically illustrated in Fig 4, and can be expressed mathematically as follows:

$$A = l*h$$

where: A ~ area of parallelogram, l = slope distance of step change,
h = perpendicular width of parallelogram.

therefore $A \;\alpha\; l$

but $l \sim d$ (for low angles)

where: d = horizontal distance of step change

therefore $A \;\alpha\; d$

and $A * w = V$

where: w = longshore segment width (conventionally taken as 1m), and V = volume moving offshore (*Voff*) or onshore (*Von).*

It was necessary to use two different types of data for the study as bar splitting and bar generation occur in different locations, the former within the surf zone and the latter upon the lower inter-tidal beach. Time-lapse images were used for the surf zone data, while ground survey maps provided inter-tidal data. The two highest resolution data sets available were used for this paper and are detailed below. However, as these data were originally collected for different research purposes, they spanned different, albeit overlapping, time periods, and the locations were separated by ~1 km. Nonetheless, these differences should not affect the comparison between bar generation and bifurcate welding, as while NOM cycles at the two sites were at times out-of-phase, overall bar behaviour was similar (Shand, 2000).

The generation of inter-tidal sand-bars, which subsequently underwent NOM, were identified from a set of morphological maps produced from ground surveys carried out at fortnightly intervals between August 1991 and March 1995. These maps cover an area 300 m longshore by 200 m cross-shore, thereby encompassing the inter-tidal beach and part of the inner bar system. Morphological features such as the saturation boundary and low tide step were defined by direct cross-shore measurement either using a tape measure or theodolite. Location errors on the maps, based on 95% confidence intervals, are estimated to be 5 m in the cross-shore direction and 10 m in the longshore direction. The fortnightly sampling interval could, theoretically, result in a systematic error, and this is discussed later in the paper.

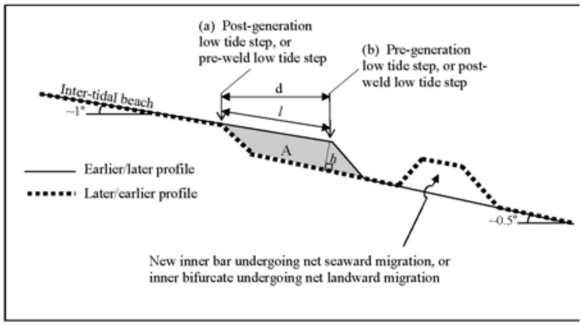

Figure 4. Schematic diagram depicting cross-shore locations of the low tide step (a) before inner bifurcate welding, or following bar generation, and (b) before bar generation, or after bifurcate welding. Components are also depicted which are used in the text to relate the distance between the step locations to the volume of displaced sediment.

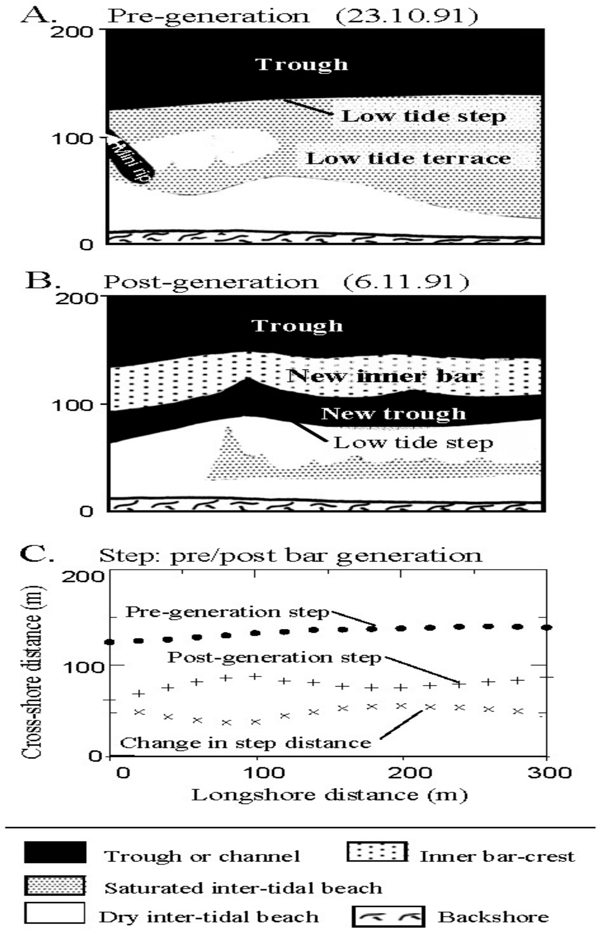

Figure 5. Morphological maps depicting a relatively featureless inter-tidal beach (A) upon which a new subtidal bar forms (B). This bar generation is the first of 4 occurrences during the study period. Comparison of the pre/post generation cross-shore positions of the low tide step are depicted in C.

Examples of maps depicting the formation of a new inter-tidal sand-bar are shown in Figs 5A and 5B, with the step locations prior to, and following, bar generation being depicted in 5C. The pre and post-generation step locations are shown in Fig 5C, and the longshore-averaged value of the change in step distance (55 m) represents sediment lost from the beach in association with this bar generation.

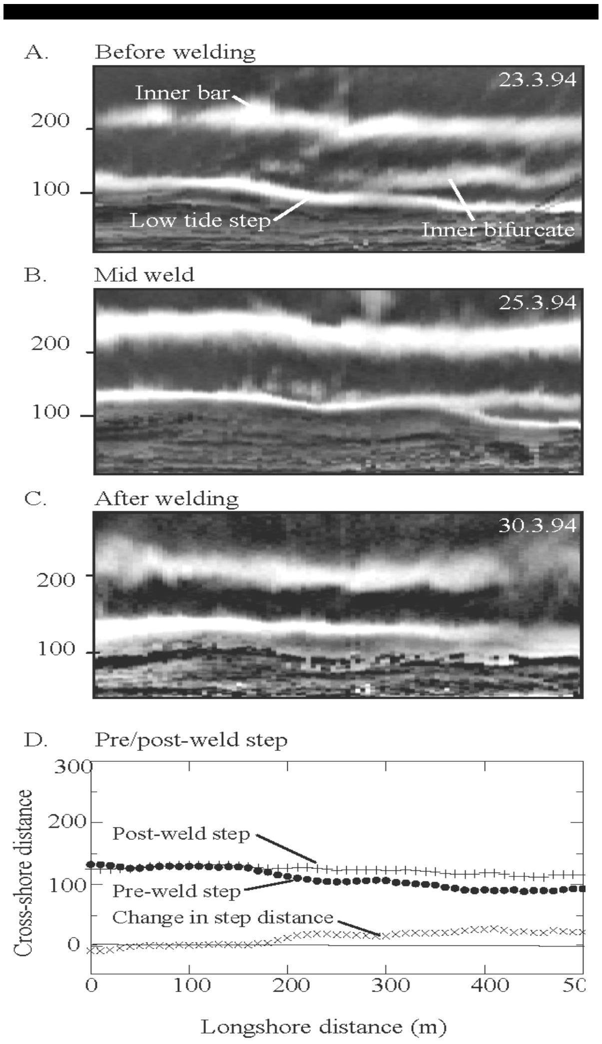

Figure 6. Sequence of rectified images depicting an inner bifurcate (A) incrementally welding to the inter-tidal beach (B and C). This episode of bar splitting was the 6th observed during the study period. A comparison of the pre/post weld cross-shore positions of the low tide step are depicted in D.

Episodes of bar splitting were identified from a 2 yr set of rectified time-lapse photographs (4 min exposures) collected between September 1991 and August 1994, and sampled at 2-5 day intervals (e.g. Fig 2). Note that time-lapse photographs are equivalent to 'time-exposure' images derived from video data that have been reported elsewhere (e.g. Aarninkhof and Holman, 1999; Bogle et al., 2000; and Morris et al., 2001). Intensity differences on time-lapse photos portray the submarine morphology, with higher intensity areas (associated with relatively intense wave breaking) representing elevated features such as bar-crests or the low tide step, and darker areas signifying deeper water such as troughs and rip channels. The camera was located on top of a 42 m high cliff and located ~130 m landward of the foredune-toe. A panorama of 4 photographs centered about the camera covered ~500 m of shoreline. Each photo was digitized, rectified to ground co-ordinates and the coastline straightened to facilitate subsequent analysis. Rectified images were clipped beyond 520 m for computer storage purposes. These techniques are described in Bailey and Shand (1996), Shand (2003), and Shand et al. (2003).

Location errors (95% confidence interval) on the rectified images for this particular site are 0 m, increasing to 12 m at the lateral extremes. In the cross-shore direction the maximum error was 15 m within the inner/mid surf zone where bar splitting occurs. While the cross-shore value (15 m) is greater than that specified above (10^0 to 10^1 m), the averaging procedure used in calculating the change in step location parameter value reduces the magnitude to acceptable levels. Eamples of images depicting an inner bifurcate welding to the foreshore are shown in Figs 6A to 6C. The pre and post-weld step locations (Fig 6D) were detected using maximum intensity values, and the longshore-averaged change in step distance (21 m) represents sediment gained by the beach from this bifurcate weld.

RESULTS

Four instances of bar generation occurred during the study period (Fig 7). The mean inter-generation period was 351 days (140 – 574 days). The mean step retreat associated with the four bar generations was 55.5 m (Table 1), and ranged between 44 and 74 m. The average bar generation retreat per inter-generation cycle will be compared with the average step advance from inner bifurcate welding per inter-generation cycle.

Table 1: Change in cross-shore location of low tide step associated with bar generation and for episodes where inner bifurcate welding affected the low tide step. Event numbers as depicted in Fig 8.

Event type	Event number and step location change (m)								Mean
	1	2	3	4	5	6	7	8	
Generations	55	44	74	49	-	-	-	-	55.5
Step welds	20	27	-	-	-	21	18	28	22.8

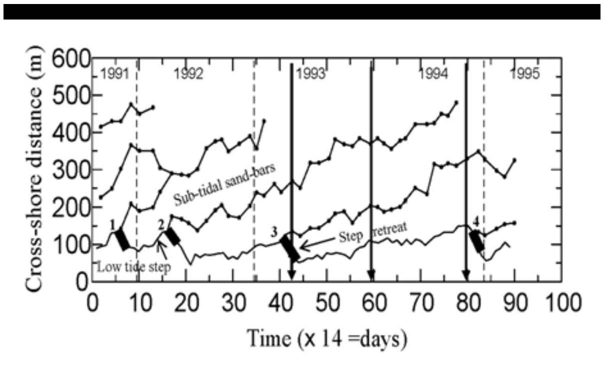

Figure 7. Bar-crest location and low tide step location time-series for cross-shore transect ~1500 m from the Wanganui Rivermouth. Four episodes of bar generation and step retreat are depicted by bold line segments. The vertical arrows mark times of sampling for the 3 images used to illustrate NOM behaviour in Fig 1.

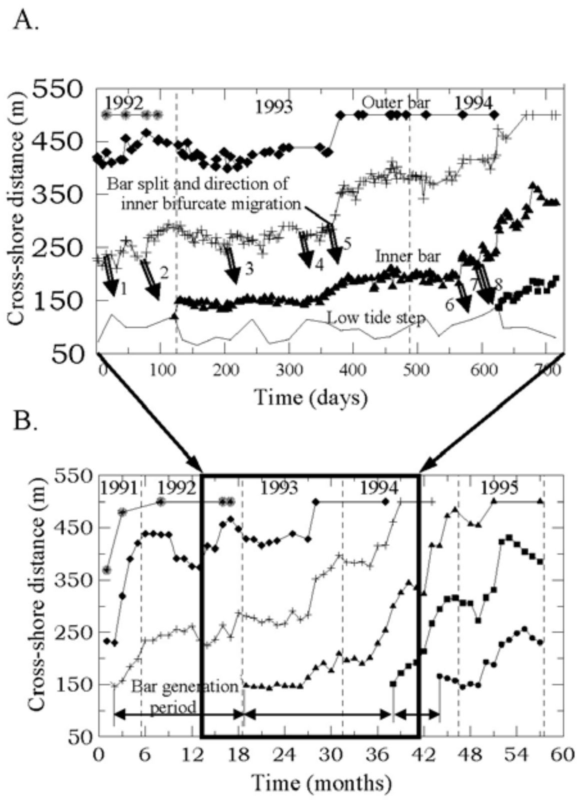

Figure 8. Time-series of bar-crest location and low tide step location for the transect located ~3000 m from the Wanganui Rivermouth. Data used in the present study are depicted in A, and the 8 episodes of bar switching are marked. A temporally extended time-series (B) is included to illustrate how the shorter-term bar and step location data, along with bar generation periods, fit within the longer-term pattern of NOM. Note outer bar migrates beyond 520 m as explained in text.

Eight episodes of bar splitting ocurred during the study (Fig 8A). Time-series graphs for each episode are depicted in Fig 9. These 8 graphs also describe the behaviour of the inner bifurcates in terms of the following: longshore coherence or incoherence of the crest; disappearance within, or transversing across, the landward trough; and fully welding to the landward bar/step during a single inter-survey period, or incrementally welding during several such periods. Only one inner bifurcate (episode 4) failed to weld. The bifurcate in episodes 3 and 5 welded to the inner bar, while the bifurcate in episodes 1, 2, 6, 7 and 8 welded to the low tide step. It is also noted that epsiodes 3 to 5 resulted from the splitting of a bar located seaward of the inner bar, and that the inner bifurcates were longshore-incoherent during much of their existence.

The 5 inner bifurcates which welded to the step did not equally affect the 500 m long study area (Fig10). Averaging the step-advances over the length of the study area resulted in 2.12 welds per metre alongshore. The assumption of longshore dispersion of localised sediment inputs is considered valid as the Wanganui coast, and indeed most NOM coasts (Shand et al., 1999), are characterised by moderate to strong longshore currents. Furthermore, the predominant longshore current direction at Wanganui is from NW to SE, i.e. right to left in Fig 10, thereby assisting with the dispersal of inner bifurcate sediment which, during the sampling period, happened to occur more often on the NW side of the study area, i.e. on the right side of graph.

When bar behaviour at the bar splitting site is compared with longer-term bar behaviour for this location (Fig 8B), it is evident that ~1.75 inter-generation periods occurred. The approximate number of welds per inter-generation period is therefore:

$$2.12/1.75 = 1.21 \text{ welds/cycle}$$

The mean step advance associated with the 5 epsiodes of welding to the inter-tidal beach = 22.8 m (Table 1) and ranged between 18 and 28 m. A similar value (23.1 m) is derived if the 2 bifurcates which welded to the inner bar are included within the calculation. The mean step advance per inter-generation cycle is therefore:

$$22.8*1.21 = 27.6 \text{ m/cycle}$$

Comparing of this value with the mean step retreat associated with the four bar generations, i.e. 27.6 m c.f. 55.5 m, suggests that approximately half (49.7%) the sediment volume lost from the inter-tidal beach during bar generation is later replaced via the process of bar splitting.

DISCUSSION

There are several limitations in the data-sets used in this study. Firstly, the 2 yr image data used to identify and analyse bar splitting contained less that 2 generation cycles and therefore may not be fully representativeof bar behaviour. However, the fact that bar splitting affected each landward bar during the study period, and that splitting occurs systematically within the NOM system, namely later in the inter-generation period when weak 3D morphologies predominate (Shand and Bailey, 1999; Shand et al., 2004), suggests that bar behaviour was probably normal during the study period.

Secondly, the 14 day sampling intervals of the bar generation data may have resulted in a systematic error in step retreat for the following reasons. Bar generation on the Wanganui coast has been observed to occur upon a wide foreshore, under neap tidal range and under storm conditions, i.e. higher waves and stronger longshore currents (Shand and Bailey, 1999; Shand et al., 2004). Bar generation would therefore tend to occur approximately one week prior to sampling which only took place during times of spring tide. However, the eastward progression of high and low pressure sytems which characterise NZ weather (Tomlinson, 1976), results in periods of fairweather following storms, conditions observed at Wanganui to be conducive to the formation of a swash bar on the lower foreshore when coupled with the typically 2D or weakly 3D new bar system (Shand et al., 2004). The subsequent landward migration of swash bars during the neap tide to spring tide change is well documented (e.g. Sonu,1972; Kroon, 1994), and the low tide step also moves landward. The position of the low tide step at sampling time would therefore over-estimate the effect of bar generation. By comparison, the higher sampling rate of the image data, used for the bar splitting exercise, avoided any systematic error in step location. The 50% sediment return to the inter-tidal beach associated with bifurcate welding therefore probably under estimates the actual value, possibly by several percent.

During the present study, other secondary morphological behaviours associated with stronger 3D topographies were identified which are capable of transfering sediment landward. For example, transverse bars, as defined by Konichi and Holman (2000), and formed, for example, when horn areas associated with (a)rhythmic morphology welds onto the beach (Wright and Short, 1984; van Enckevort et al., 2004), may detach from the inner bar and the 'free arm' realign in the direction of the longshore current. The arm then either dissipates within the trough, or migrates landward to weld with the step in the same manner as the inner bifurcate from bar splitting. There is evidence of such a 'detached transverse bar' process within the ellipses marked on the left hand side of the images in Figs 2B and 2C, and the resulting seaward extension of the step is evident when the distances in Figs 2C and 2D are compared.

The occurrence of 3D morphologies therefore appears to play a

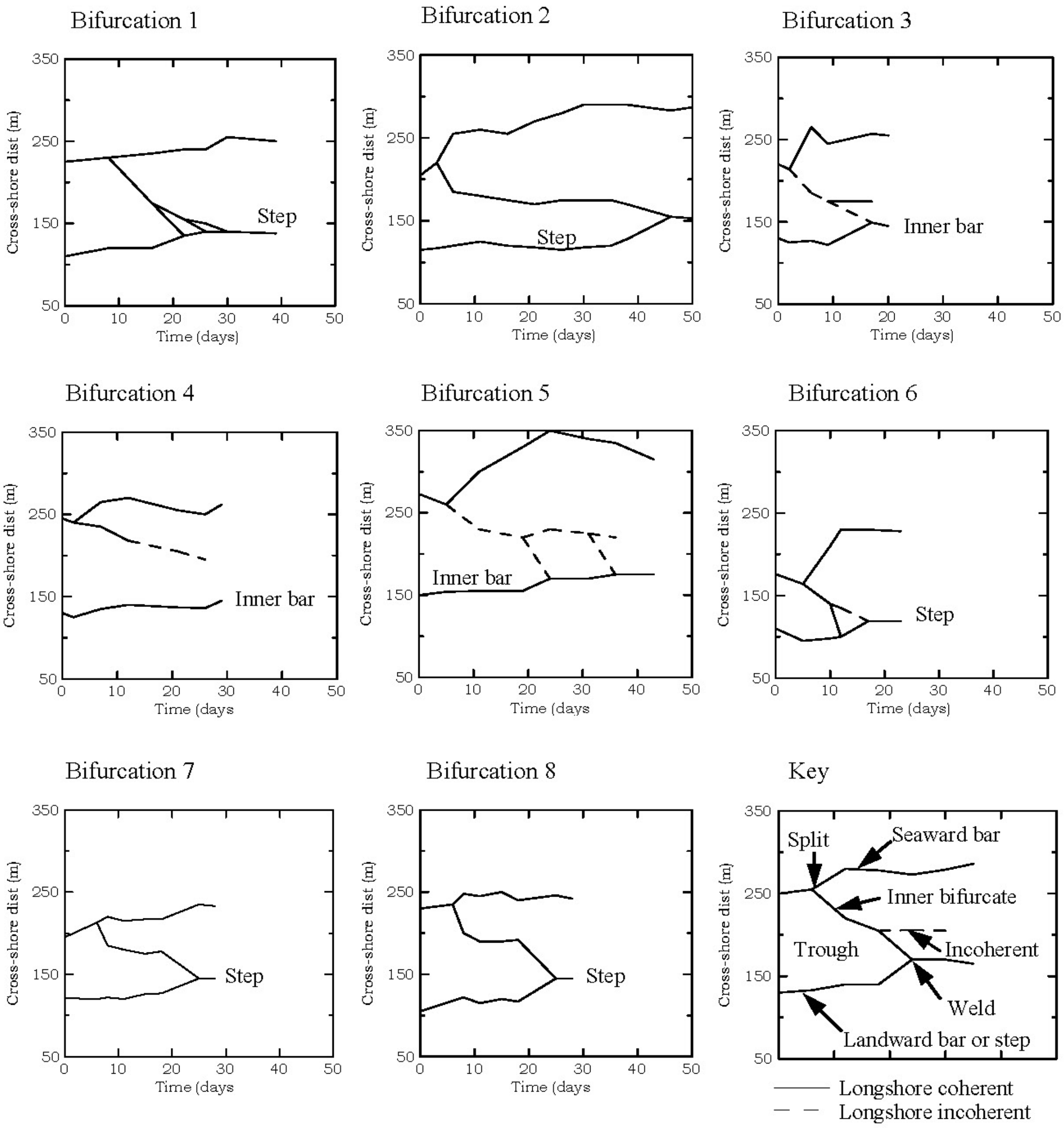

Figure 9. Bar-crest location time-series for the 8 bifurcations (bar splits) which occurred during the 2 yr study period. Each graph also depicts the behaviour of the inner bifurcate in terms of the following: longshore coherence/incoherence of crest; disappearance within, or traversing across, the landward trough; fully welding to the landward bar/step during a single inter-survey period, or incrementally welding during several such periods. The timing of these episodes of bar splitting are marked in Fig 8.

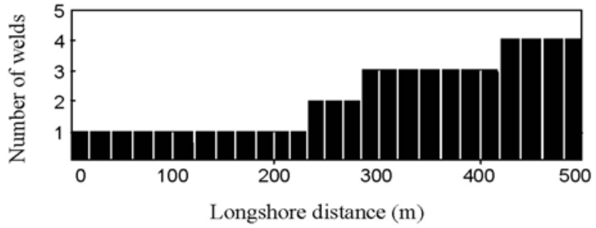

Figure 10. Histogram depicting inner bifurcate welds along study site.

key role in the development of landward-migrating secondary sand bodies. At Wanganui, 3D configurations occur earlier in the NOM cycle when the bar is still within the inner surf zone (Shand, 2002). During this time, incident energy is dissipated (filtered) on a well-developed seaward bar (Shand et al., 2004), thereby facilitating 3D pattern development via self-organisational behaviour.

Integration of the findings from this paper with those in the other referenced work, enabled the formulation of a conceptual morphodynamic model of cross-shore sediment transport mechanisms for the NOM system at Wanganui (Fig 11). The model is primarily based on research from Wanganui with results from other sites have also been incorporated. The model is expected to have application at other NOM coasts. Of additional interest is the depiction in Fig 11B of the inner bar moving seaward while ripped (stronger-3D) states predominate (see Shand, 2004). During this period which may last several months, sediment appears to move offshore via the continually reforming and/or longshore migrating rip channels.

The inclusion of 3D configurations within the conceptual morphodynamic model presented in Fig 11, contrasts with previous models for NOM systems (Ruessink and Kroon, 1994; Wijnberg, 1995; Ruessink and Terwindt, 2000; Kuriyama, 2002)

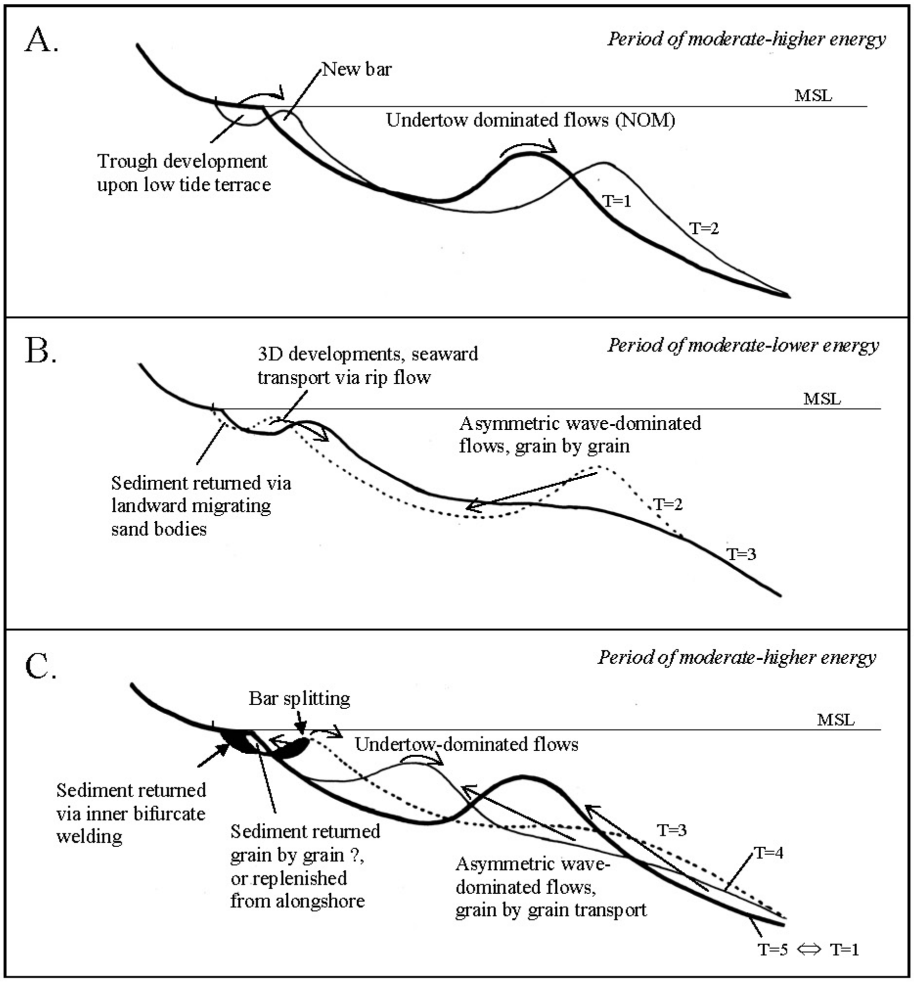

Figure 11. **11** A conceptual model of sediment transport mechanisms for the NOM system at Wanganui. At time T=1, the profile contains a single sub-tidal sand-bar. At T=2, an additional bar has formed. The sequence terminates at T=5 at which time the new bar has reached the cross-shore location of the bar at T=1. The ‘return period’ of the system is thus defined by T=5. The processes depicted in the diagrams are either described, or referenced, within the text.

which are entirely 2D. The systematic occurrence of several types of 3D behaviour, enables a significant portion of sediment within the inner-mid surf zone to move shoreward and thus help counter any sediment imbalance associated with the underlying process of NOM. In addition, the systematic occurrence of rip-channels, provide an additional mechanism to undertow-driven seaward sediment transport within the inner surf zone. Finally, it is noted that existing inter-annual process-based modeling (e.g. Roelvink et al., 1995; Aarninkhof, 1998?) will need to incorporate 3D non-linear dynamical behaviour if the NOM system is to be numerically replicated.

CONCLUSIONS

This study used ground survey and image-based data-sets from Wanganui, New Zealand, to show that shoreward sediment transport within landward migrating inner bifurcates (associated with bar splitting), account for at least half of the inter-tidal beach sediment which is lost seaward in association with bar generation. While bar splitting occurs upon weak to moderate 3D topographies, other types of behaviour associated with stronger 3D antecedent morphologies were identified during the study which are capable of transfering further sediment landward within migrating sand-bodies. Landward migrating secondary bars therefore appear to play a significant role in returning sediment to the inter-tidal beach. Some sediment will also be added to the beach from longshore transport, and the possibility still exists that a portion of sediment returns via grain by grain processes within the inner surf zone. A conceptual morphodynamic model of the NOM system is presented in which 3D behaviour is an essential component, in contrast to existing models which are entirely 2D.

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REFERENCES

AARNINKHOF, S., and HOLMAN, R.A., 1999. Monitoring the nearshore with video. Backscatter, 10, 8-11.

BAUER, B.O., and GREENWOOD, B., 1990. Modification of a linear bar-trough system by a standing edge wave. Marine Geology, 92, 177-204.

BAILEY, D.G., and SHAND, R.D., 1996. Determining large-scale sand bar behaviour. *Proceedings of the IEEE International Conference on Image Processing*, Lausanne, Switzerland, (2), 637-640.

BIRKEMEIER, W.A., 1984. Time scales of nearshore profile change. *Proceedings of the 19th International Conference on coastal Engineering*, ASCE, pp. 1507-1521.

BOGLE, J.A.; BRYAN, K.R.; BLACK, K.P.; HUME, T.M.; and HEALY, T.R., 2000, Video observations of rip formation and evolution. *Journal of Coastal Research Special Issue 34*, 117-127.

DE VROEG, J.H.; SMIT, E.S.P., and BAKKER,W.T., 1988. Coastal Genesis. *Proceedings of the 21st International Conference on coastal Engineering*, ASCE, pp. 2825-2839.

DONOHOE, B.F.P., 1998. *Spatial and temporal bar morphodynamics of Muriwai Beach*. MSc thesis, Auckland University, New Zealand, 104p.

GALLAGHER, E.L.; ELGAR, S.; and GUZA, R.T., 1998. Observations of sand bar evolution on a natural beach. *Journal of Geophysical Research*, 103, 3203-3215.

GREENWOOD, B., and DAVIDSON-ARNOTT, G.D., 1975. Marine bars and nearshore sedimentary processes, Kouchibouguac Bay, New Brunswick. In: Hails, J., and Carr, A., (eds.), *Nearshore Sediment Dynamics and Sedimentation.* John Wiley and Sons, New York, pp. 123-150.

GREENWOOD, B., and DAVIDSON-ARNOTT, R., 1979. Sedimentation and equilibrium in wave formed bars: a review and case study. *Canadian Journal of Earth Science*, 16, 312-332.

HAXEL, J.H., and HOLMAN, R.A., 2004. The sediment response of a dissipative beach to variations in wave climate. *Marine Geology*, 206, 73-99.

HOEFEL, F., and ELGAR, S., 2003. Wave-induced sediment transport and sandbar migration. *Science*, 299, 1885-1887.

HOLMAN, R.A., and LIPPMANN, T.C., 1987. Remote sensing of nearshore bar systems - making morphology visible. *Proceeding of Coastal Sediments'87*, ASCE, pp. 927-944.

HOLMAN, R.A., and SALLENGER, A.H., 1986. High energy nearshore processes. *EoS Trans. AGU* 67, 1369-1371.

HOUSER, C., and GREENWOOD, B. 2004. Profile response of a lacustrine multiple barred nearshore over a sequence of storm events. *Geomorphology*, 69, 118-137.

HOUWMAN, K.T and RUESSINK, B.G., 1996. Cross-shore sediment transport mechanisms in the surfzone on a time scale of months to years. *Proceedings of the 25th International Conference on Coastal Engineering,* ASCE, pp. 4793-4806.

KONICKI, K.M., and HOLMAN, R.A., 2000. The statistics and kinematics of transverse sand bars on an open coast, *Marine Geology*, 169, 69-101.

KROON, A., 1991. Three-dimensional morphological changes of a nearshore bar system along the Dutch coast near Egmond aan Zee. Proceedings of the Skagen Symposium, *Journal of Coastal Research, Special Issue, 9*, 430-451.

KROON, A., 1994. *Sediment transport and morphodynamics of the beach and nearshore zone near Egmond, The Netherlands*. PhD thesis, Utrecht University, the Netherlands, 275p.

KROON, A., and HOESKSTRA, P., 1993. Nearshore bars and large-scale coastal behaviour. In: List, J.H., (ed.), *Large-Scale Coastal Behaviour '93*. U.S. Geological Survey, Open-File Report 93-381, pp. 92-95.

KURIYAMA, Y., 2002. Medium-term bar behaviour and associated sediment transport at Hasaki, Japan. *Journal of Geophysical Research*, 107.

KURIYAMA, Y., and LEE J.H., 2001. Medium-term beach profile change on a bar-trough region at Hasaki, Japan, investigated with complex principal component analysis. In *Proceedings Coastal Dynamics '01,* ASCE, pp. 959-968.

LARSEN, M., and KRAUS, N.C., 1992. *Analysis of cross-shore movement of natural longshore bars and material placed to create longshore bars*. Technical Report CERC DRP-29-5, 115p.

LIPPMANN, T.C.; HOLMAN, R.A., and HATHWAY, K.K., 1993. Episodic, nonstationary behaviour of a double bar system at Duck, North Carolina, U.S.A., 1986-1991. *Journal of Coastal Research, Special Issue, 15*, 49-75.

MORRIS, B.D; DAVIDSON, M.A., and HUNTLEY, D.A., 2001. Measurements of the response of a coastal inlet using video monitoring techniques. *Marine Geology*, 175, 251-272.

ROELVINK, J.A.; MEIJER, J.G.P.; HOUWMAN, K.; BAKKER, R., AND SPANHOFF, R., 1995. Field validation and application of a coastal profile model. *Proceedings of Coastal Dynamics'95*, ASCE, pp. 818-828

RUESSINK, B.G., 1998. *Infragravity waves in a dissipative multiple bar system.* PhD thesis, Utrecht University, the Netherlands, 245p.

RUESSINK, B.G., and KROON, A., 1994. The behaviour of a multiple bar system in the nearshore zone of Terschelling, the Netherlands: 1965-1993. *Marine Geology*, 121, 187-197.

RUESSINK, B.G., and TERWINDT, J.H.J, 2000. The behaviour of nearshore bars on a time scale of years: a conceptual model. *Marine Geology*, 163, 289-302.

SHAND, R.D., 2000. Offshore *migration of coastal sand-bars at Wanganui, New Zealand*. PhD thesis, School of Global Studies, Massey University, New Zealand, Miscellaneous Publication Series, 00/8, 295p.

SHAND, R.D., 2002. *Temporal variation in morphological configuration within a multi-bar surf zone at Wanganui, New Zealand*. Occasional Paper 2002/4, School of People Environment and Planning, Massey University, New Zealand, 42p.

SHAND, R.D., 2003. Relationships between episodes of bar switching, cross-shore bar migration and outer bar degeneration at Wanganui, New Zealand. *Journal of Coastal Research*, 19(1), 157-170.

SHAND, R.D., 2004. *Rip-associated bathing hazards on beaches characterised by net offshore bar migration*. Occasional Paper 2004/1, School of People Environment and Planning, Massey University, New Zealand, 19p.

SHAND, R.D., and BAILEY, D.G., 1999. A Review of Net Offshore Bar Migration with Photographic Illustrations from Wanganui, New Zealand, *Journal of Coastal Research*, 15(2), 365-378.

SHAND, R.D.; BAILEY, D.G., and SHEPHERD, M.J., 1999. An inter-site comparison of net offshore bar migration characteristics and environmental conditions. *Journal of Coastal Research*, 15(4) 750-765.

SHAND, R.D., BAILEY, D.G., and SHEPHERD, M.J., 2001. Longshore realignment of nearshore parallel sand-bars at Wanganui, New Zealand. *Marine Geology* 179, 147-161

SHAND, R.D.; HESP, P.A., BAILEY, D.G., and SHEPHERD, M.J., 2003. A conceptual beach-state model for the inner bar of a storm-dominate, low to moderate tidal range coast at Wanganui, New Zealand. *Proceedings of Coastal Sediments '03.*

SHAND, R.D.; HESP, P.A., and SHEPHERD, M, J., 2004. Beach cut in relation to net offshore bar migration. *Journal of Coastal Research, Special Issue 3*, in press.

SONU, C.J., 1972. Field observation of nearshore circulation and meandering currents. *Journal of Geophysical Research*, 77(18), 3232-3247.

SVENDSEN, I. A. 1984. Mass flux and undertow in a surf zone. *Coastal Engineering*, 8, 347-365.

TOMLINSON, A.I., 1976. Climate. In Woods, I. (ed.) *New Zealand Atlas*, Government Printer, New Zealand, pp. 82-89.

VAN ENCKEVORT, I.M.J.; RUESSINK, B.G.; COCO, G.; SUZUKI, K .; TURNER, I.L.; PLANT, N.G., and HOLMAN, R.A., 2004. Observations of nearshore crescentic sandbars. *Journal of Geophysical Research* , 109, 1029-1046.

WIJNBERG, K.M., 1995. *Morphologic behaviour of a barred coast over a period of decades*. PhD thesis, Utrecht University, the Netherlands, 245p.

WIJNBERG, K.M., 1996. On the systematic offshore decay of breaker bars. *Proceedings of the 25th International Conference on Coastal Engineering*, ASCE, pp. 3600-3613.

WIJNBERG, K.M., and TERWINDT, J.H.G., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Marine Geology*, 126, 301-330.

WRIGHT, L.D., and SHORT, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology*, 56, 93-118.Wright, L.D.; Nielsen, P,; Shi, N.C., and List, J.H., 1986. Morphodynamics of a bar-trough surf zone. *Marine Geology*, 70, 251-285.