Conceptual beach-state model for the inner bar of a storm-dominated, micro/meso tidal range coast at Wanganui, New Zealand

R.D. Shand[1]; D.G. Bailey[2]; P.A. Hesp[3], and M.J. Shepherd[1]

Abstract

Plan-view morphological configurations were identified for the inner sub-tidal bar at Wanganui, New Zealand, and configuration behaviour was related to wave height, longshore current (in terms of longshore wind components), tidal range (in terms of neap tide-spring tide variation), and antecedent morphology to derive a conceptual model for this type of coast. The Wanganui coast is characterised by fine sand, multiple sand bars, frequent storm waves, longshore current, a neap tidal range of 0.8 m and a spring tidal range of 2.4 m. Transverse configurations occur more frequently and were more persistent than the other 3 types of configuration used in the study: linear, undulating and subdued. The predominant class transitions consist of transverse configurations changing to subdued and undulating; undulating configurations changing to transverse; linear configurations changing to undulating, and subdued configurations changing to transverse. Configuration change to transverse, undulating and linear occur under lower (neap) tidal conditions, with linearity increasing with increasing wave height and strength of the longshore current. Change to subdued configurations corresponds with higher (spring) tides, lower wave height and weaker longshore current. The direction of longshore currents also influences configuration change. In particular, the formation of transverse configurations are facilitated by longshore currents aligned with the oblique rip currents which characterise the Wanganui coast. By contrast, the formation of subdued and undulating configurations appear to be facilitated by longhore currents opposing obliquely orientated rip currents. Morphological feedback enables transverse configurations to resist greater wave height and stronger longshore current than occur during their formation. While undulating and linear configurations remain coherent during higher tidal range, bar-crests broaden in the cross-shore direction with the opposite occurring during times of lower tidal range. Transverse configurations may also persist during higher tidal range; however, in this situation bar-crest broadening and channel infill can result in a class change to subdued configurations.

INTRODUCTION

Sand-bar plan-view configurations on sand-dominated coasts depend on the energy regime, sediment characteristics and physical boundary conditions. This paper is

1) Geography Programme, Massey University, Private Bag 11222, Palmerston North, New Zealand, r.d.shand@clear.net.nz
2) Institute of Information Sciences and Technology, Massey University, Private Bag 11222, Palmerston North, New Zealand.
3) Department of Geography and Anthropology, Louisiana State University, Baton Rouge, LA 70803-4105, United States of America, pahesp@lsu.edu

concerned with configurations of the landwardmost (inner) sub-tidal bar on the Wanganui coast of the New Zealand North Island This is a multi-bar coast characterised by fine sand, storm waves, micro-meso tidal range (as defined by Davies, 1980), and longshore currents. In a recent study of daily to monthly configuration change at Wanganui, Shand (submitted) found that bar behaviour within the mid surf zone was consistent with the Short and Aagaard (1993) model, a comprehensive configuration-based conceptual model for multi-bar coasts with micro tidal range. However, the Short and Aagaard model did not account for bars in the outer surf zone at Wanganui becoming subdued and disappearing, this being the final stage in the process of net offshore bar migration (see Shand and Bailey, 1999). Furthermore, inner bar behaviour at Wanganui had several characteristics which differed from the Short and Aagaard model and these differences form the basis of the present paper.

The inner bar component of the Short and Aagaard multi-bar model is the frequently referenced Wright and Short (1984) morphodynamic model for single bar beaches. The Wright and Short model describes sub-tidal bars as moving seaward and becoming linear during higher energy conditions, this configuration or state being termed ‘longshore bar and trough’ in their model. As wave energy subsequently decreases, the bar migrates landward and develops an undulating configuration (‘rhythmic bar and beach’ state). Gradually, transverse bars develop between the undulating bar and the inter-tidal beach, with attachment points being separated by rip channels (‘transverse bar and rip’ state). Morphological feedback is important in these recovery processes. The model is also characterised by non-linear structures tending to have both symmetry about shore-normal axes and regularity in longshore spacing. Under extended fair-weather conditions the bar system continues to migrate landward to fully merge with the inter-tidal beach and form ‘ridge and runnel’ or ‘low tide terrace’ configurations.

Differences between the Wanganui inner bar study (Shand, submitted) and the Wright and Short model are now described. Cross-shore bar migration at Wanganui did not respond to changing levels in wave energy; this is possibly a consequence of wave energy filtering by the seaward bar(s). While the bar did become linear under higher wave conditions and become strongly non-linear (transverse bars and rips) under lower waves, there was not a statistically significant difference in wave height separating the formation of undulating and linear configurations. Subdued configurations with an average cross-shore width of ~100 m occurred at Wanganui. These features are substantially wider than the most subdued morphology in the Wright and Short model, i.e. low tide terraces. This situation suggests that tidal range can be important in morphodynamic processes at Wanganui. Finally, it was found that only 8% of non-linear configurations at Wanganui were symmetrical about shore-normal axes, a result which indicates longshore currents play a significant morphodynamic role.

The purpose of the present paper is to develop a conceptual beach-state model for the inner bar at Wanganui at a time-scale of days to months, and to incorporate variation in incident wave height, tidal range (in terms of neap tide/spring tide change), longshore currents and antecedent morphology. Configurations are determined by developing and applying a mutually exclusive classification scheme to a 2 yr set of time-exposure images.

FIELD SITE

The 500 m long field site is ~3 km from the Wanganui Rivermouth on the southwestern coast of the North Island of New Zealand (Fig 1). The nearshore is characterised by fine sand (2 to 3 phi), and has a cross-shore slope of ~0.0085 and width of ~550 m. Three sand-bars are usually present; these bars undergo net offshore migration, with the mean life-cycle of a bar being ~3 yr (Shand et al., 1999). The camera used for photographing the surf zone was located on top of a 42 m high cliff which lies 100 m to the rear of the beach.

The process conditions are summarized as follows. The mean neap tide range = 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 (Macky et al., 1988). 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 25% (Patterson, 1992). Five years of daily wave observations, which encompassed the study period, show 42% of waves approach from the west, 24% from the south and 34% lie within one degree of shore-normal. Longshore current measurements made using floats released into the inner surf zone as part of a Port Development Study (Patterson 1992), found the mean current = 0.42 m/s and the 5% excedence value = 1.01 m/s. Analysis of wind data collected at nearby Wanganui Airport, shows prevailing winds approach the coast at ~35 deg from the shoreline. The 5% excedence value for the wind speed is 12.4 m/s. The longshore wind component is strongly correlated with the longshore current ($p < 0.001$).

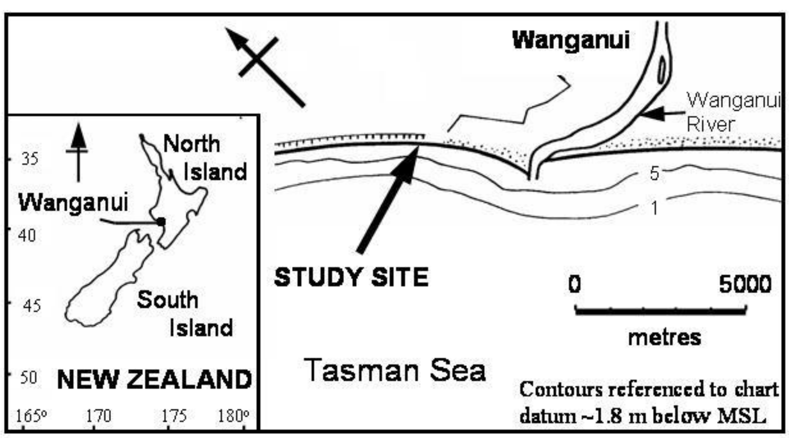


Figure 1 Location map of the Wanganui study site.

METHODS

The following methods used to derive morphological and process data for this study have been described in greater detail by Shand (submitted).

A panorama of 4 photographs captured the 500 m long study area. Each photo was exposed for 4 mins to minimise tidal change experienced during sampling and to ensure a relatively stable representation of the breaking wave pattern. Such photographs are equivalent to images produced by time-averaging video frames (Lippmann and Holman, 1989). These images provide an analogue for surf zone morphology because elevated topography such as sand-bars are characterised by locations of higher intensity due to waves breaking preferentially in shallower water (Lippmann and Holman, 1989). An example of a time-exposure panorama which encompasses the study site, is shown in the upper portion of Fig 2.

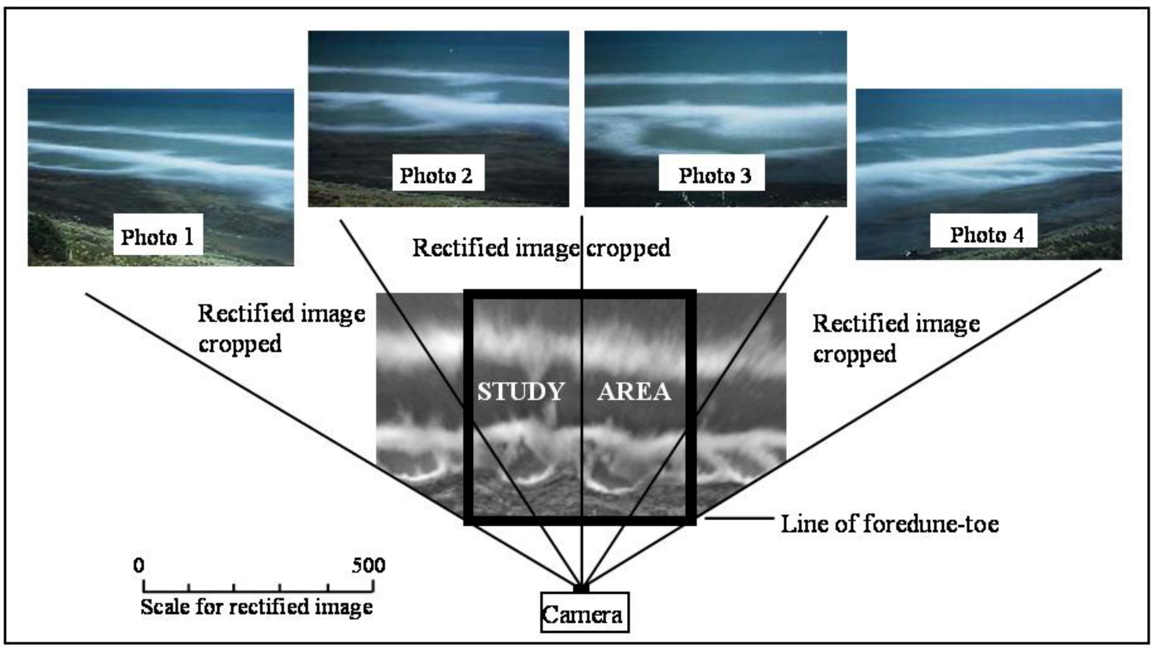


Figure 2. An example of a panorama of 4 time-exposure photographs (above), and the corresponding rectified and merged images (below). Areas of high intensity represent elevated features such as sand-bars, and the intermediate areas of low intensity represent rip channels and longshore troughs Two hundred metre wide segments of rectified image have been retained at the longshore margins of the 500 m long study site to assist in the interpretation of 3D structures.

This study utilizes a 2 yr set of photographs collected between September 1992 and August 1994. Field sampling was carried out at ~4 day intervals (standard deviation = 2 days), with more frequent sampling occurring during times of higher energy to detect faster morphological change.

Digital image processing was used firstly to rectify each photograph to ground co-ordinates, secondly to merge this rectified image with adjacent rectified images from the panorama, and thirdly to transform the image mosaic to achieve a straightened coastline. These techniques have been described in detail by Bailey and Shand (1993, 1996). An example of the final output image is shown in the lower portion of Fig 2.

Intensity maxima only approximate a bar-crest location as environmental conditions and bar morphology influence break-point location. For the present study, maximum errors (using the 95% confidence interval) are 15 m in the cross-shore direction and 12 m in the longshore direction.

Configurations were based on a mutually exclusive, shape-based, classification scheme similar to that of Lippmann and Holman (1990). Alternative procedures involve morphological assemblages (e.g. Wright and Short, 1984; Short and Aagaard 1993), complex eigenfunctions (Ruessink et al., 2000), or cross-shore deviations between the longshore bar-crest and a fitted linear model (van Enckevort and Wijnberg, 1999). However, these approaches were not considered because they require regular and relatively simple 3D morphologies, whereas non-linear configurations at Wanganui are predominantly irregular and often complex.

The following three criteria, and associated binary decisions shown within brackets, were used to categorise different intensity patterns (morphological configurations) associated with the sub-tidal inner bar at Wanganui:

- cross-shore bar profile relief (pronounced c.f. subdued);
- longshore variability (linear c.f. non-linear) of a longshore bar-crest;
- longshore variability (continuous c.f. discontinuous) of the trough, i.e. region of low intensity values located landward of a bar.

In addition, several other qualifiers are detailed in Shand (submitted) which were applied to ensure consistency when applying the classification scheme.

Four classes were defined to represent the morphologies contained within the image data-set. These morphological classes are identified using the following descriptors: subdued, linear, undulating and transverse, and an example of each is shown in Fig 3. Linear configurations are broadly equivalent to both the 'longshore bar and trough' in the Wright and Short model and 'bar types F and G' in the Lippmann and Holman (1990) classification. Undulating configurations are broadly equivalent to 'rhythmic bar and beach' (Wright and Short) and 'bar type E' (Lippmann and Holman), while transverse configurations are broadly equivalent to 'transverse bar and rip' (Wright and Short) and 'bar types C and D' (Lippmann and Holman). Subdued configurations have the appearance of either a wide area containing very low amplitude features or a wide terrace; this differs in scale and in some cases it also differs in form to Wright and Short's 'ridge and runnel/low tide terrace' and Lippmann and Holman's 'bar type B'.

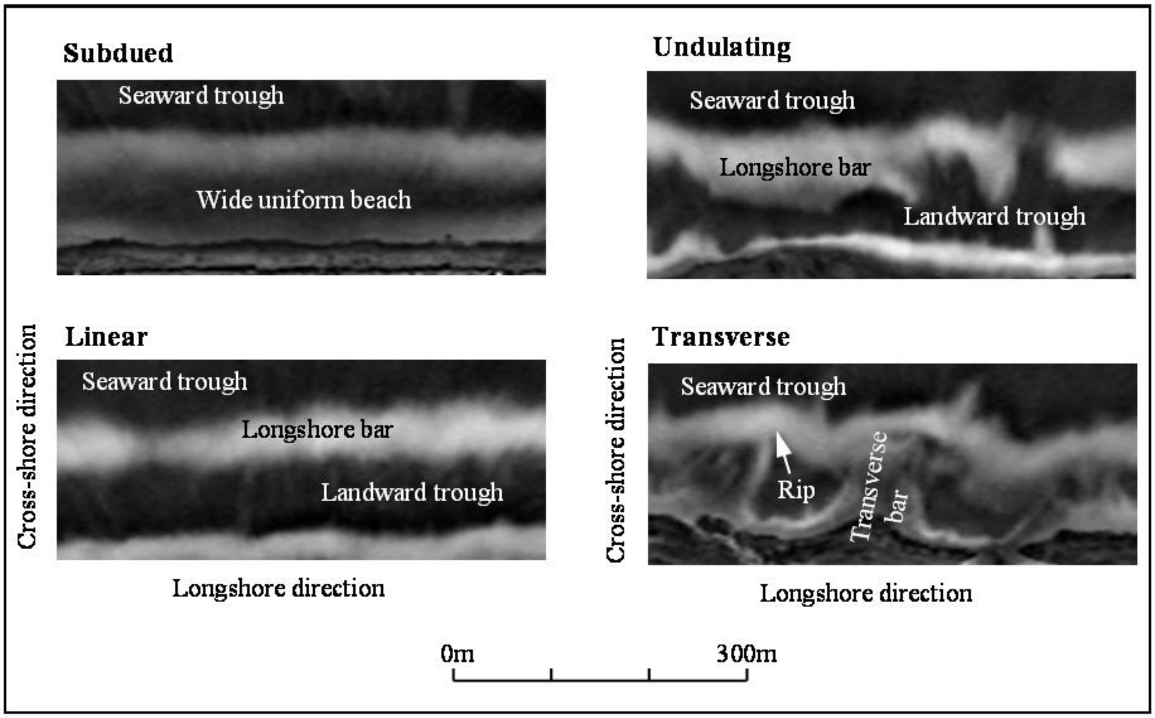


Figure 3 Examples of morphologies corresponding to the 4 configuration classes derived in the text.

Different types of configuration could occur contemporaneously at different locations within the 500 m long study site, so the modal class for each sample, i.e. the class with the greatest longshore length, was used for analysis. Furthermore, errors of up to 100 m were observed in the (longshore) length assigned to a particular class under the range of tide and wave conditions experienced during the study. So modal class status was only assigned when the length was at least 100 m greater than that of any other configuration class present within a sample. These procedures resulted in 124 inner bar samples being available for subsequent analysis.

Wave height data consisted of daily observations made at the break-point using the 'staff and horizon' method described in, for example, Patterson and Blair (1983), and Horikawa (1988). The inter-survey maximum (daily) wave height was the wave-based parameter used for analysis.

The longshore wind component has been identified as a suitable surrogate, in terms of variation, for the longshore current (Nummedal and Finley, 1978), and this approach is used in the present study. The longshore wind speed corresponding to the maximum inter-survey wave height was used in analysis, because the effectiveness of longshore current in sediment transport depends on the corresponding wave height (Komar and Inman, 1970; Hardisty, 1990). Three-hourly longshore wind measurements were averaged over the 9 hours prior to the relevant wave height measurement to account for wind fluctuation.

Official tide data were used to determine tidal range at the time of maximum inter-survey wave height.

RESULTS and DISCUSSION

The frequencies (percentages) and residence times (persistence) for the different types of configuration are depicted in Figs 4A and B respectively. Transverse configurations occurred most frequently (55%), followed by undulating (17%), subdued (15%) and linear (13%). Transverse were also the most persistent configuration (mean = 12.6 days) followed by subdued (mean = 9.25 days), linear (mean = 5.7 days) and undulating (mean = 5.2 days).

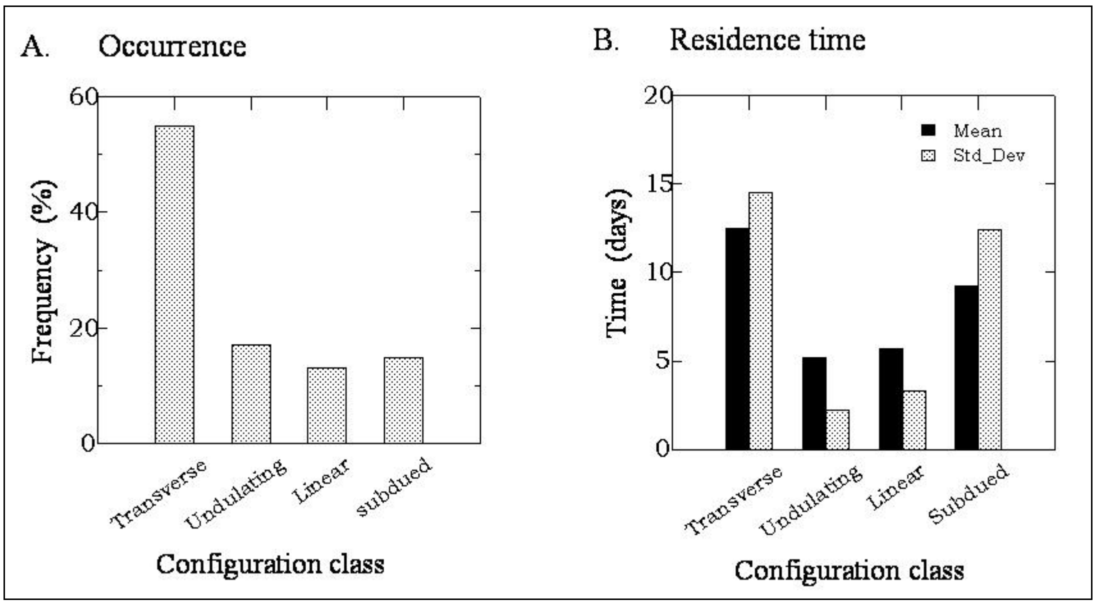


Figure 4 Frequencies (A) and, mean and standard deviation of residence times (B) for configuration classes.

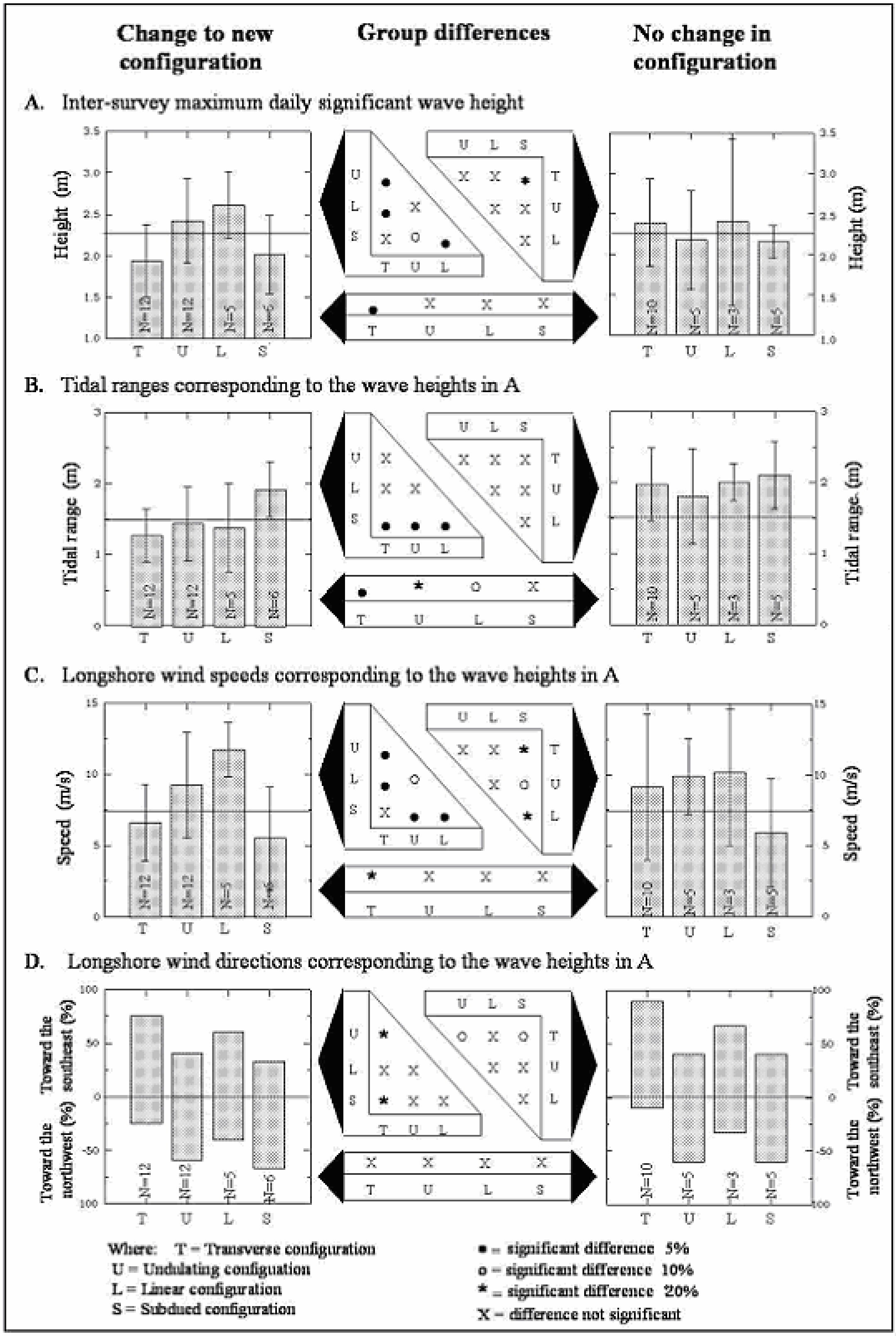
Numbers and percentages of transitions between different configurations are shown in Table 1. Transverse configurations tended to change to either undulating (42%) or subdued (42%), while both undulating and subdued configurations tended to change to transverse (82% and 75% respectively). These results show configurations preferentially fluctuate between transverse and undulating, and also between transverse and subdued. A small percentage of each of these configuration changed to linear, while linear configurations changed primarily (66.6%) to undulating. There was therefore little tendency for transverse configurations to change directly to linear by omitting or 'jumping' the undulating state. Such jumps in configuration were observed by Lippmann and Holman (1990) within the inner bar at Duck, North Carolina, and rapid 'up-state' behaviour characterises the Wright and Short single bar model. The contrasting behaviour at Wanganui will be considered further later in this section.

Table 1. Transitions from configuration classes at top of table to configuration classes on left side of table.

	Transition From			
Transition To	Transverse	Undulating	Linear	Subdued
Transverse	+	9 (82%)	2 (33%)	6(75%)
Undulating	8 (42%)	+	4 (67%)	1 (12.5%)
Linear	3 (16%)	2 (18%)	+	1 (12.5%)
Subdued	8 (42%)	0 (0%)	0 (0%)	+

Wave height, tide range and wind conditions corresponding to inter-survey periods in which configuration change occurred, and also to periods in which no configuration change occurred, are depicted in Figure 5. Graphs on the left represent configuration change, while graphs on the right represent no configuration change. Two-sample t-tests were used to determine whether differences in wave height (A), tidal range (B) or longshore wind speed (C) values for different configurations within each graph were statistically significant. These test results, in terms of the 5%, 10% and 20% levels of significance, are denoted by symbols within the matrices located between each pair of graphs. The lower matrix compares environmental conditions associated with the same type of configuration in each pair of graphs. It is noted that the t-test assumption of sample normality was met in that all skewness values were non-significant. To evaluate the longshore wind direction data, either two-sample Chi-square tests, or Fisher exact probability tests were used depending on sample size and size of the expected frequencies (Siegel, 1956).

The results (Fig 5A) show similar wave heights occurred during class changes to transverse and subdued configurations, but significantly higher values occurred during class changes to undulating and linear configurations. These results have been reproduced from Shand (submitted) and, as noted earlier in the introduction, they are broadly consistent with the Wright and Short model. For undulating, linear and subdued



Change to new configuration
Group differences
No change in configuration
A. Inter-survey maximum daily significant wave height
Height (m)
B. Tidal ranges corresponding to the wave heights in A
Tidal range (m)
C. Longshore wind speeds corresponding to the wave heights in A
Speed (m/s)
D. Longshore wind directions corresponding to the wave heights in A
Toward the southeast (%)
Toward the northwest (%)
Where: T = Transverse configuration
U = Undulating configuation
L = Linear configuration
S = Subdued configuration
● = significant difference 5%
o = significant difference 10%
* = significant difference 20%
X = difference not significant

Figure 5 Graphs depicting process variable values associated with inter-survey changes to new configurations are shown on the left of the figure, while graphs depicting values associated with no change in configuration are shown on the right. The vertical error bars in A-C represent one standard deviation about the mean which is represented by the bar height. The statistical significance of differences in process variable values associated with different configurations, are depicted by the symbols contained in the centrally located matrices. The upper left matrix within each set of three matrices, relates to the graph depicting changes to new configurations, the upper right matrix relates to the graph depicting no change in configuration, and the lower matrix relates to the same type of configuration in each graph. The types of statistical test used for these assessments are described within the text.

configurations, wave heights during periods when no configuration change occurred were statistically similar to wave heights during periods when change to these classes occurred. In contrast, wave heights during periods when no transverse configuration change occurred were significantly different (greater) than wave heights which occurred during the formation of such configurations. This result indicates that in some situations, strongly non-linear configurations can resist wave energy otherwise capable of increasing their linearity.

Tidal range results (Fig 5B) show the 3 pronounced configuration types tend to form under lower (neap) tide conditions, results consistent with the Wright and Short model for micro tidal beaches. However, subdued configurations form during times of higher (spring) tide. So, while both transverse and subdued morphologies form under lower wave conditions, they require contrasting tidal range. This tidal influence at Wanganui comes despite the relative tidal range (RTR), i.e. the ratio of the mean spring tide range to the modal breaking wave height which equals 1.85 at Wanganui, being below both the theoretical threshold (2.0) determined by Masselink (1993), or the field-based threshold (3.0) identified by Masselink and Short (1993). The graph on the right of Fig 5B, shows that all configuration types could survive the morphological smoothing effect other research has associated with a higher tidal range (e.g. Wright et al., 1987; Masselink , 1993). However, while linear and undulating bar-crests will not broaden to the extent of causing a change in state (Table 1), troughs and rip channels in the vicinity of transverse configurations may infill to the extent that a change to subdued configuration occurs (Table 1).

Longshore wind results (Fig 5C) are similar to the wave height results in that lower speeds occur during class change to transverse and subdued configurations, while higher speeds occur during change to undulating and linear configurations. It is noted that linear configurations occur under significantly higher longshore winds, and hence stronger longshore currents, than those which occur during the formation of undulating configurations; this difference was not statistically significant with the configuration change-associated wave data in Fig 5A. The longshore wind speed during periods in which no configuration change occurred are also similar to the wave height results, with transverse configurations being able to resist significantly higher winds (stronger longshore current) than occurred during the formation of these configurations. The influence of strongly non-linear configurations on both the longshore and wave induced current fields, and hence on the persistence of such configurations, must reflect morphological feedback processes and free or self-organised behaviour as defined by, for example, Southgate and Beltran (1998).

Such morphological feedback may explain why strongly non-linear configurations at Wanganui tend not to change directly to linear configurations as noted earlier. In addition, the tendency for rapid and direct upstate transitions during higher wave conditions on single bar coasts and at Duck, may reflect the higher proportion of incident energy able to reach the (inner) bar due to the lack of filtering by seaward bars. Note that Duck has only a single seaward bar compared with more than one at Wanganui (Shand et al., 1999). Alternatively, the more rapid morphological change at single bar sites and at Duck, may be associated with lower tidal range and/or smaller sand-bar volumes (Shand et al., 1999).

The effects of morphological control, together with the influences of changing wave height, longshore current and tidal range, on morphological configurations at Wanganui, together with the effects of morphological control, are conceptualised in Fig 6.

The direction of longshore wind (longshore current) results in Fig 5D, show transverse configurations were more likely to occur under southeasterly directed (toward the rivermouth) winds, while undulating and subdued configurations tended to occur under northwesterly directed winds. A similar and somewhat more enhanced pattern is evident in the longshore wind directions which occurred during periods in which no configuration change occurred. The association between southeasterly directed longshore currents and the formation of transverse configurations may result from an antecedent morphological imprint with a southeasterly directed offset. It seems likely such an imprint would occur as Shand (submitted) showed that 69% of non-linear configurations at Wanganui were skewed toward the southeast and that this was directionally consistent with the long-term longshore wind pattern. Such an imprint would facilitate transverse development as the longshore current would be aligned with, and hence enhance, currents within oblique depressions or mini-rips. Further morphological control is suggested by the formation of undulating and subdued configurations, which, as noted earlier, develop exclusively from transverse configurations (Table 1). In this situation, northwesterly directed longshore currents would oppose the southeasterly skewed rip currents, thereby disrupting the underlying cellular flow and lead either to the occurrence of undulating configurations, by erosion of the transverse bar from the lower foreshore under lower tidal conditions, higher wave heights and stronger longshore currents, or to the occurrence of subdued configurations by the infill of rip channels under conditions of higher tide range, lower wave height and weaker longshore currents.

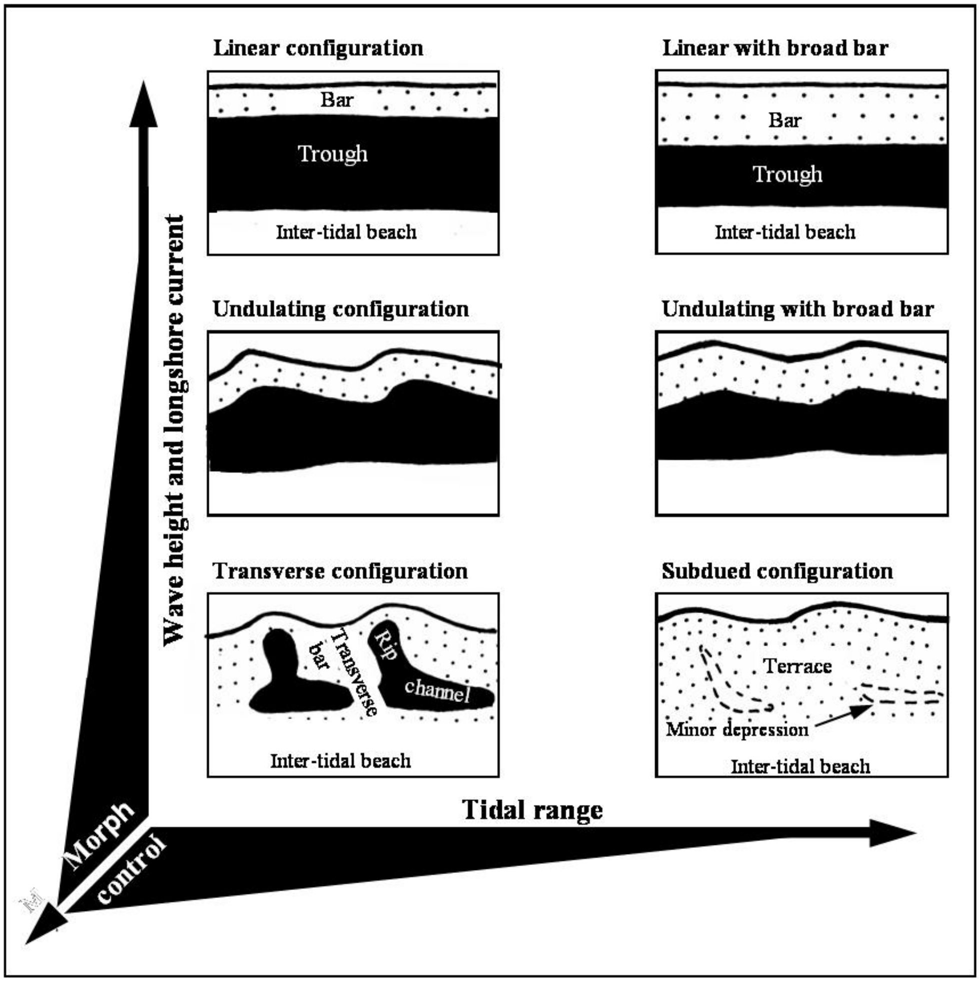


Figure 6 Schematic representation of morphological configurations and their relationship to wave height, longshore current and tidal range. The relative importance of morphological control associated with different configurations is also depicted.

CONCLUSIONS

A configuration plan-view analysis was carried out on a 2 year image-based data-set of the landward sub-tidal bar at Wanganui, New Zealand. The identified morphological behaviour was then related to wave height, longshore current (via the longshore wind component), tidal range (in terms of neap tide-spring tide variation), and antecedent morphology to derive a conceptual model for this type of coast. Transverse configurations occur more frequently and were more persistent than the other 3 types of configuration: linear, undulating and subdued. The predominant class transitions consist of transverse configurations changing to subdued and undulating; undulating configurations changing to transverse; linear configurations changing to undulating, and subdued configurations changing to transverse.

Configuration change to transverse, undulating and linear occur under lower (neap) tidal conditions, with linearity increasing with increasing wave height and strength of the longshore current. Change to subdued configurations corresponds with higher (spring) tides, lower wave height and weaker longshore current. The direction of longshore currents also influences configuration change, with the formation of transverse configurations being facilitated by longshore currents which are aligned with the oblique rip currents that characterise the Wanganui coast. By contrast, the formation of subdued and undulating configurations appear to be facilitated by longhore currents which oppose obliquely orientated rip currents. Morphological feedback enables transverse configurations to resist greater wave height and stronger longshore current than occur during their formation. While undulating and linear configurations remain coherent during higher tidal range, bar-crests broaden in the cross-shore direction with the opposite occurring during times of lower tidal range. Transverse configurations may also persist during higher tidal range; however, in this situation bar-crest broadening and channel infill can result in a class change to subdued configurations. Future quantitative morphodynamic modelling will need to incorporate interactions between 3D morphologies and obliquely orientated rip channels, tidal range (in terms of neap tide-spring tide variation) and longshore currents when considering coastal environments similar to that at Wanganui.

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