An inter-comparison of hindcast and measured wave data: implications for beach recharge design

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Introduction

Hindcast wave climates typically form the basis for the derivation of hydrodynamic design conditions for beach management schemes. Wave climate data is typically derived for periods of several decades, where suitable model or wind data exists. Extreme design conditions are determined in deepwater conditions using extrapolation of probability distributions of hindcast data. Techniques such as the 3-parameter Weibull distribution are used to identify events of defined return periods; these are subsequently transformed to nearshore shallow water locations, which are often subject to depth limited conditions under the more extreme events.

Extreme design wave climate data are often used in the design of stability of coastal structures, or to examine the cross shore response of beaches in storm conditions. Similarly, time series of several years transformed hindcast data may be used to derive morphological averaged conditions or nearshore time series to drive numerical or physical sediment transport models. The design of beach recharge schemes is usually developed using a variety of models, including numerical, physical and empirical approaches; these are analysed on the basis of anticipated performance of the beach under a variety of defined extreme nearshore conditions. The majority of hydrodynamic design methods use model input based on simple integrated parameters of significant wave height (H_s), zero crossing wave period (T_z), peak spectral wave period (T_p) and direction and (at the most sophisticated) a standardised spectral shape typical of the site.

It is valuable to the designer to understand the sensitivity of beach performance to each of the design variables. An improved understanding of the significance of error, or variability of hydrodynamic conditions, will assist the developers of wave models by providing evidence of the need to improve forecasting, hindcasting or transformation techniques, where this is required.

This investigation examines the design and post construction performance of a beach recharge scheme using such typical design approaches. The site is located on the central south coast of the UK (Figure 1) at Hurst Spit (Bradbury and Kidd, 1998). Reference is made to 13 years of post construction monitoring and comparison of measured conditions with the original design wave climate. The scheme has a beach recharge design life of 10 years and so the whole of this design period has been examined and the scheme performance can be compared with the pre-scheme expectations.

This paper examines

- Typicality of the hindcast offshore wave climate used in the design phase (1974-

1990) with hindcast data for the post design and post construction period (1988-2006).
- Comparison of the measured wave climate derived at a shallow water (10-12m) wave buoy with a co-located hindcast and transformed wave climate for the period 1996-2009.
- Identification of key differences in measured and hindcast wave climate and storm characteristics
- Examination of the implications of differences in modelled and measured wave climate with measured beach performance between1996-2009.

Although recent advances have improved the modelling capability of hindcasting models, more mature schemes (such as that discussed in this paper) have been designed on the basis of less sophisticated models and sometimes over much shorter durations than is desirable. More recently developed schemes have the opportunity to benefit from both lengthy records and from increasingly sophisticated hindcasting and wave transformation modelling methods.

Long-term post scheme monitoring has been undertaken to assess the effectiveness of the wave climate design tools and where appropriate suggest where modifications are required to either definition of design conditions, or improvement of the design tools. Broader scale implications of the findings have been considered on a regional basis. A range of design variables and system responses have been assessed based on an extensive long term monitoring programme. The significance of each of the following are considered within the paper.

- Wave climate characteristics
- Beach evolution and longshore transport
- Cross shore beach response

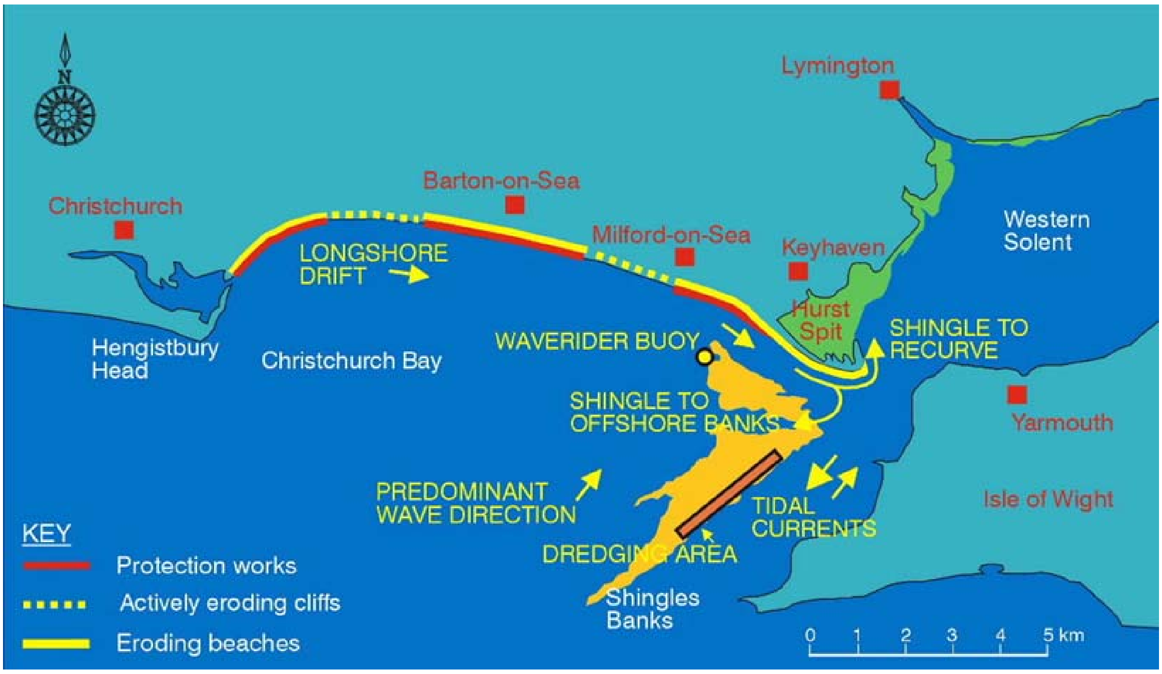

Figure 1 Location plan

Wave climate characteristics

Offshore wave climate

Two offshore time series, generated by hindcasts at the offshore boundary, have been determined from separate models; these cover the design phase and the subsequent post design, construction and post-construction phases.

A design offshore wave climate for Christchurch Bay was derived for the beach management scheme design phase, based on a hindcast for the period 1974-1990. The HR hindwave model (HR Wallingford, 1989a) was used to determine the wave climate used in the beach management scheme design; it does not include swell within its formulation. This was complemented by a short period of direct measurement from a buoy at Milford-on-Sea (Hydraulics Research 1989a and b). Extreme wave conditions were determined for events with a range of return periods. The offshore wave climate was subsequently transformed to suitable nearshore locations in about 10-12m water (see below).

A second hindcast was conducted using the Met Office European waters model to cover the post design and post construction periods; this covers the period 1988-2006. The Met Office model includes swell generation within the 2nd generation model. Further, the Met Office model has been refined during the investigation period. Finer resolution data (UK waters 12km grid) is available for part of the period although the data used for determination of extremes in this investigation is based upon the 25km grid model which covers the whole of the period 1988-2006. A comparison of various time series is illustrated for an event, within a time series period of one week, with an exceedance probability of about 10 times per year, using both model resolutions. Figure 2 identifies outputs at the offshore boundary in about 30m water depth. Outputs from two different resolutions of the Met Office model are compared. These indicate that the peak conditions are about 10-15% lower in the coarser resolution (25km) model relative to the finer resolution (12km) model. This appears to be reasonably typical of the more stormy conditions.

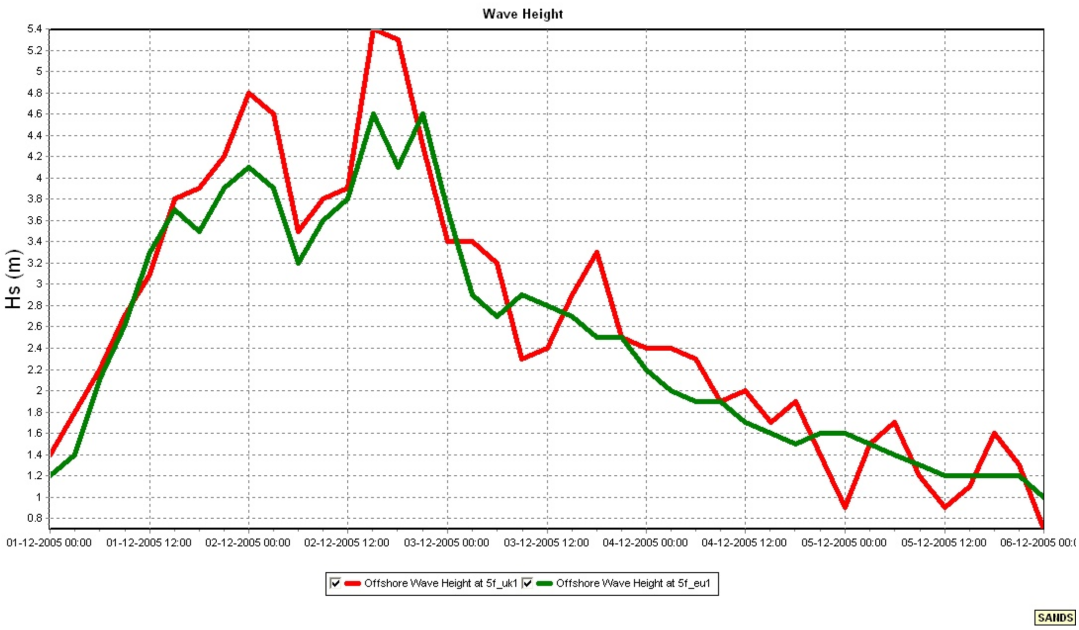

Figure 2 Comparison of hindcast time series outputs for 12km and 25km resolution Met Office models at offshore boundary.

There is a reasonable expectation therefore, that the differing methodologies may produce slightly differing results. Direct comparison of data from an overlapping period of 3 years (1988-1990) suggests that the Hindwave and Met Office 25km grid models produce remarkably comparable outputs however, both for H_s and T_z.

The extremes determined from the two hindcasts at the offshore boundary are compared (Figure 3). The period from 1988-2006 appears to have been somewhat more stormy than the period 1974-1990. The estimated 1:100 year return period significant wave height (H_s) event, extrapolated using the Weibull analysis based on probability distribution for the period 1974-1990, was 7.9m; this compares with an H_s of 9.3m for the period 1988-2006. The maximum significant wave height derived from the hindcast for the period 1974-1990 was 7.2m, by comparison with 8.2m for the period 1988-2006. Data for the two models have not been combined to provide a continuous time series, due to the different modelling approaches. Although the durations used to develop the extremes analysis (17 and 19 years) are not ideal, they are typical of many hindcasts used in engineering design.

The implication is that the 1:100 year return period significant wave height determined in 1990 appears to be representative of a return period of about 1:8 years, determined in 2006. The design implication is that the scheme has been tested to a much lower standard return period than was intended during the design phase.

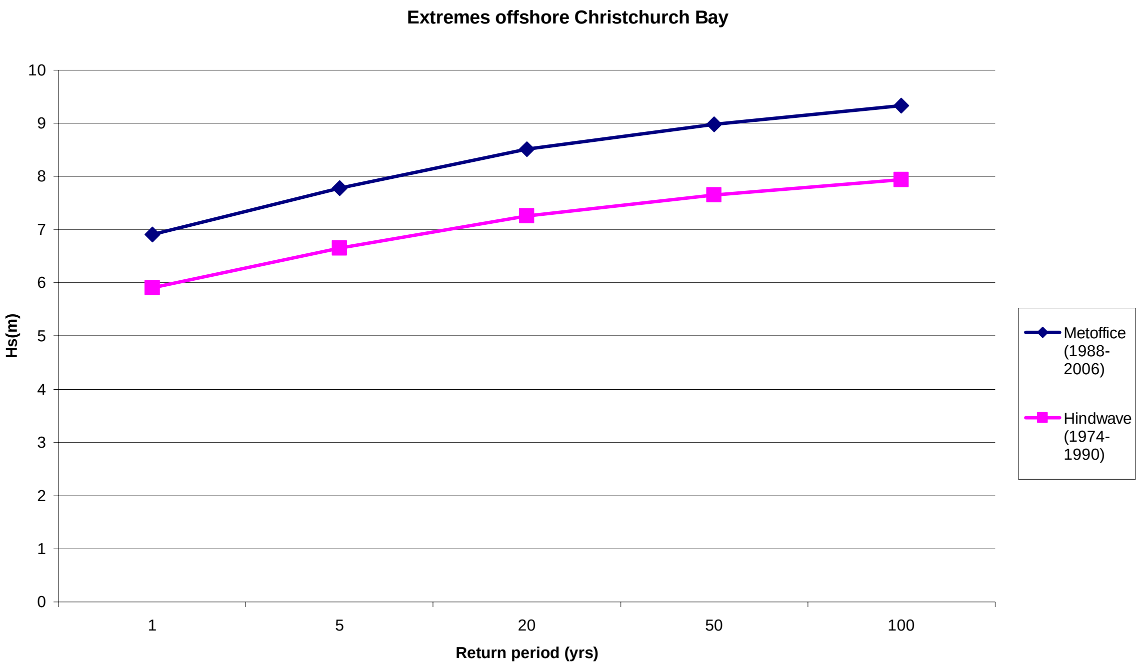

Figure 3 Comparison of Weibull distribution extrapolations for Hs at the Christchurch Bay offshore boundary, based on offshore hindcasts for the periods 1974-1990 and 1988-2006.

Nearshore conditions – validation of modelling

The long term deployment of a wave-rider buoy at one of the nearshore prediction points has formed the basis of evaluation of the wave climate modelling methods. Comparisons have been made for the whole of the post construction period from1996-2006, during which co-located measured data and transformed hindcasts are available. Synoptic post construction comparisons of measured and modelled wave data at the Milford-on-Sea wave buoy site

(1996-2006) are shown (Figure 4). The measured data is compared with transformed data from the Met Office 25km wave model. The analysis includes both comparison of bulk statistics for each of the key integrated parameter variables and also comparison of short time series (Figures 5-7) to examine the differences between both storm events and more regularly occurring conditions.

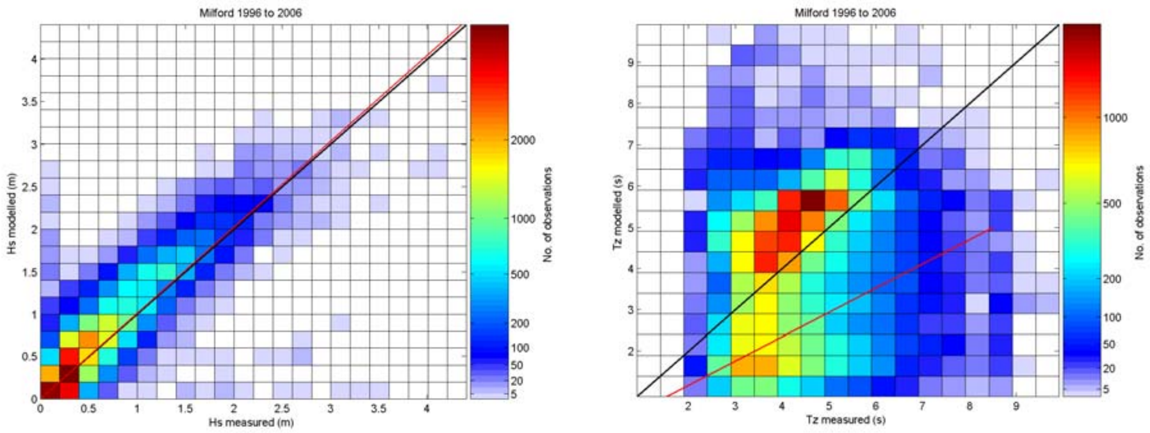

Figure 4 Comparison of modelled and measured distribution of H_s and Tz at Milford-on-Sea (1996-2006) (from Bradbury et al 2009).

Significant differences in wave climate characteristics are evident between modelled and measured wave conditions. The models typically over predict significant wave height (H_s) conditions when H_s <2m, whilst the extreme events are slightly under predicted. By contrast, the comparison of wave period (T_z) suggests that the model typically overpredicts wave period by about 20%, although the data is very widely scattered. This scatter is broadly attributed to the low frequency resolution of the Met Office model. These patterns are both typical of systematic differences observed between modelled and measured data at a network of wave buoy sites along the English Channel (Bradbury et al, 2004). This implies wider ranging significance of these observations at many sites where model data have been used for design.

A comparison of various time series, including H_s, T_z and Direction is illustrated for an event, within a time series period of about one week (Figures 5-7). The peak of the event has an exceedance probability of about 10 times per year.

The time series highlights typical variability between the modelled and measured conditions (Figure 5). The model typically overpredicts H_s for conditions where H_s<2m. The timing of peaks is consistently very well predicted by the model. This is consistent with earlier observations of regional trends based on bulk statistics (Bradbury et al 2004). Similarly, the peak values associated with infrequently occurring severe events H_s>3m seem to be slightly underpredicted by the model.

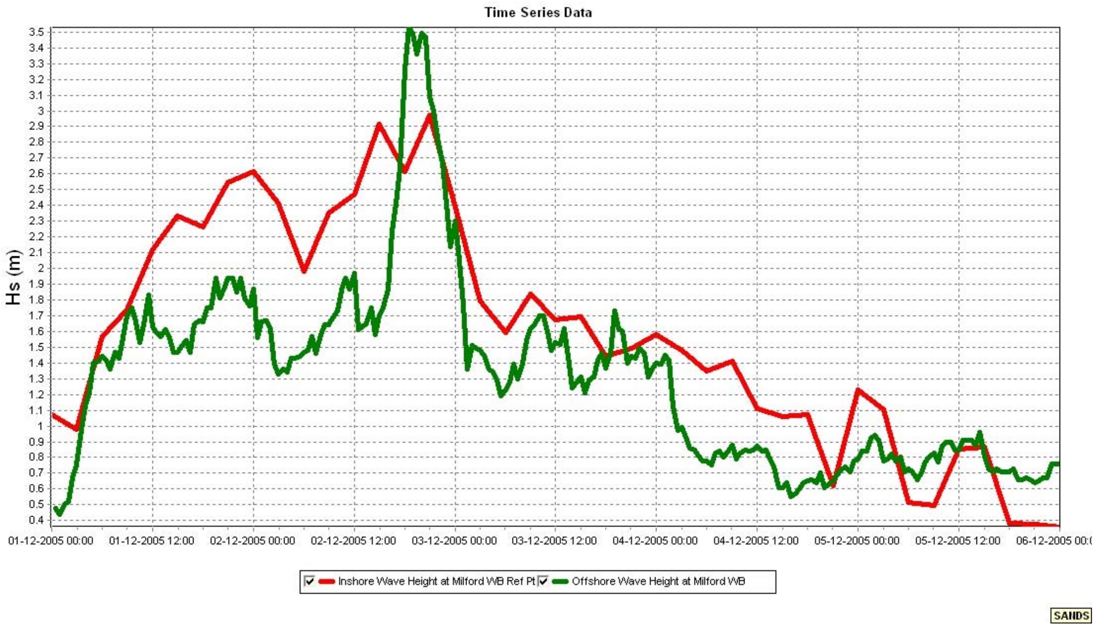

Figure 5 Comparison of co-located measured and modelled time series of significant wave heights for a typical storm at Milford waverider buoy site following scheme construction.

By contrast, the wave period modelling appears to be somewhat less precise. Although bulk statistics suggest very wide scatter of the results, analysis of short sections of time series (Figure 6) indicate that the model appears to overpredict wave period by about 20% on a regular basis.

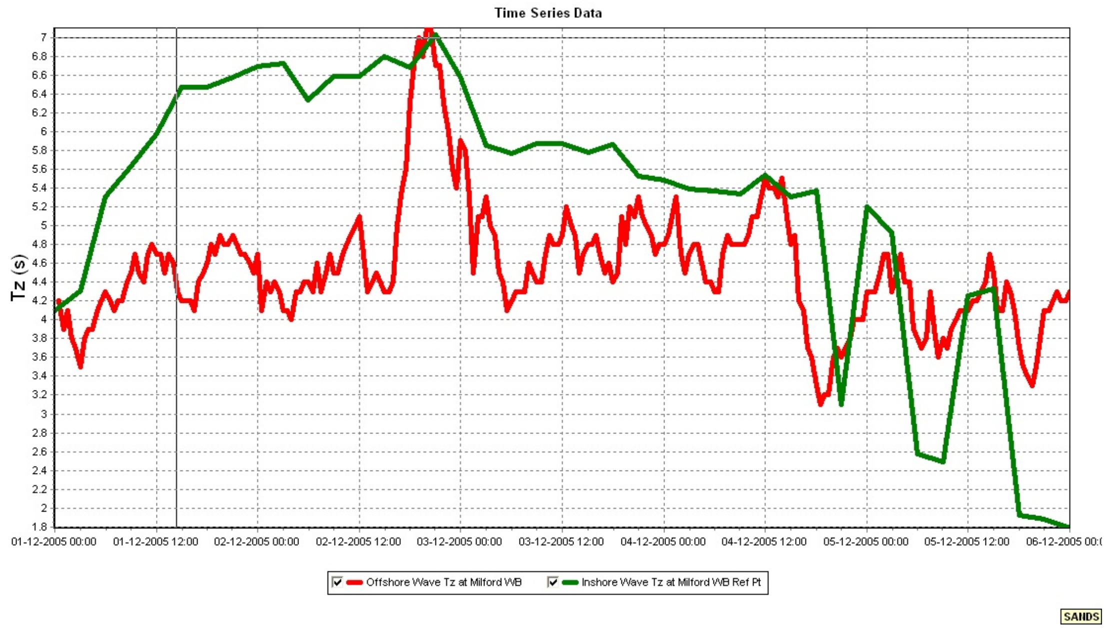

Figure 6 Comparison of co-located measured and modelled time series of zero crossing period for a typical storm at Milford waverider buoy site following scheme construction.

The modelling of wave direction appears to relate reasonably well with measured data (Figure 7), although there is some clear evidence of scatter. The variance of measured and modelled conditions regularly reaches 10^{O}.

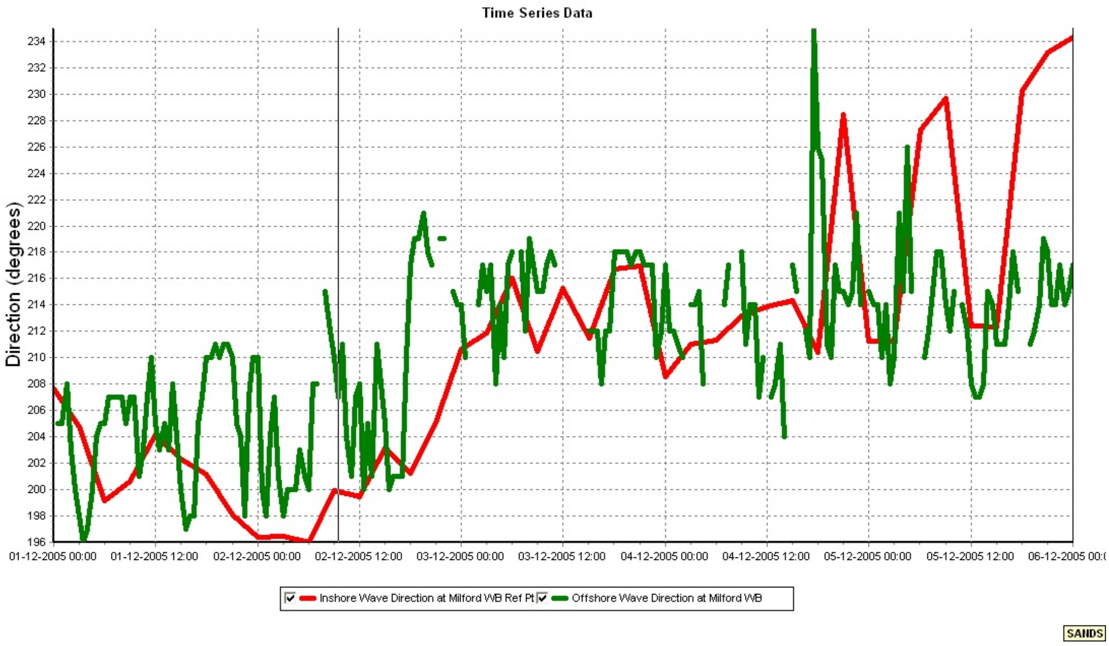

Figure 7. Comparison of co-located measured and modelled time series of wave direction for a typical storm at Milford waverider buoy site following scheme construction.

Nearshore design conditions

The nearshore extreme wave conditions used in the beach management design process were determined by transforming conditions from the offshore hindcast boundary to a series of nearshore sites, including the buoy site, where conditions are anticipated to be depth limited under the most extreme conditions. This provides an appropriate method for determination of nearshore extremes. Application of a standard probability density function at this boundary, based on the measured time series, is likely to provide an over-prediction of extremes because of the depth limiting effects at the site. The nearshore conditions vary considerably along the length of the site, due to the complex bathymetry and shelter afforded by complex offshore bank formation. This has major implications for the calculation of sediment transport rates and necessitates a range of nearshore wave prediction locations. The focus of this investigation is on the wavebuoy site however.

The nearshore extreme conditions calculated by transformation of the extrapolated hindcast 1:100 return period offshore event, for the waverider buoy site are defined by:

H_s=3.34 T_z=9.2s

Wave periods associated with the extreme conditions were based on the assumption that wave steepness would be comparable with the more extreme events in the statistical record of hindcast events.

Variability of post construction conditions

The measured data suggests that the transformed theoretical 1:100 year return period event has been exceeded in three consecutive years, as demonstrated by the 0.05% exceedance level observations; this implies that the sample period of model data used for scheme design has either been too short, is not representative of more recent conditions, that the model under-predicts extreme conditions or a combination of these. These observations are consistent with the direct comparisons of offshore hindcasts, which suggest that the post construction period has been significantly rougher than the period used to develop the design conditions. This suggests that the actual design conditions used are representative of conditions that are somewhat more frequently occurring than the desired 1:100 year event. It should be noted that the shallow water prediction site limits wave heights. The measured 10% exceedance level is comparable with the suggested design wave climate (1.5m) however. The extrapolated 1:100 year return period (design) event, based upon extrapolated offshore hindcast data transformed to the waverider location, is shown in Figure 8; this is compared with post construction probability distributions of measured wave conditions at the same location from 1996-2007.

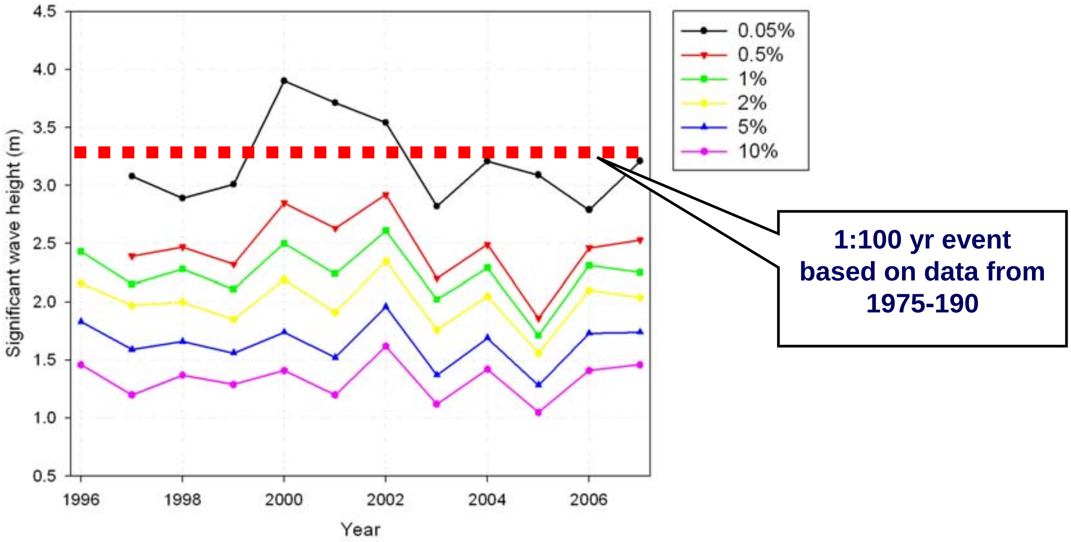

Figure 8 Extreme wave climate compared with post construction observations of probability distributions at Milford-on-Sea wave rider buoy site. (from Bradbury et al 2009)

Storm event analysis

The frequency and distribution of individual storm events is considered by reference to Figure 9; this highlights the distribution of measured storm events over the period 1996-2008. Each event has been extracted from the measured time series on the basis of a clearly-defined events-over-threshold method. This is compared with the theoretical 1:100 year return period H_s at this location.

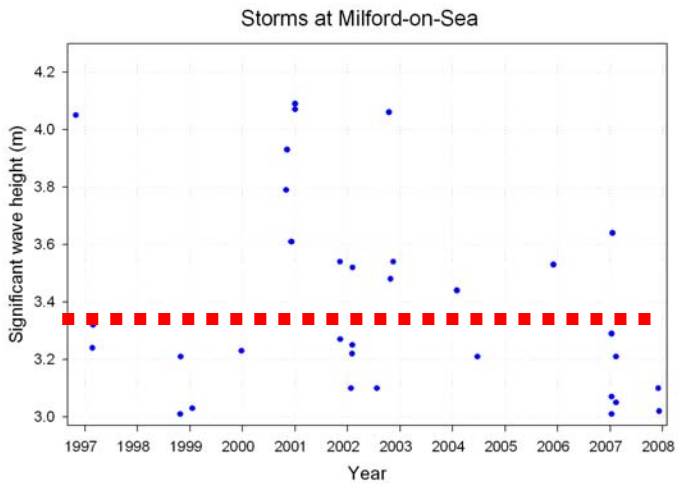

Figure 9 Design conditions compared with post construction observations of storm events at Milford-on-Sea wave rider buoy site.

This method of data presentation is particularly valuable as a metric for consideration of the impacts of sequencing of storm events on beach management.

An event by event comparison is made of modelled and measured H_s for post construction storm events above a threshold condition of 2.5m (Figure 10). This confirms the general observation identified within the bulk statistics; that extreme conditions with measured H_s>3.5m are generally under represented by the modelling approach. It also provides further confirmation that the design conditions used are not representative of a 1:100 year return period event (Bradbury et al, 2009).

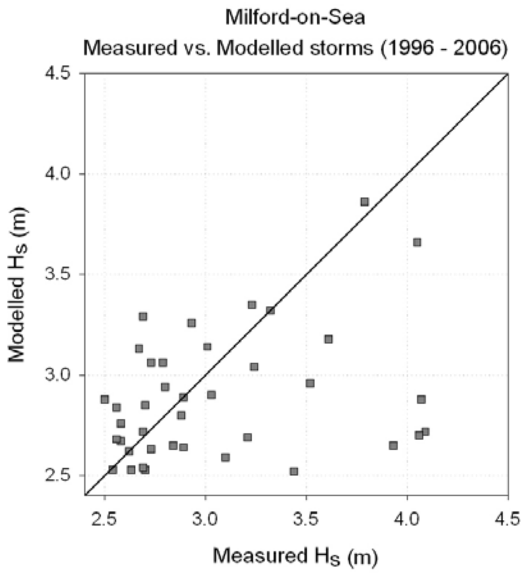

Figure 10 Post construction comparison of measured and modelled storm events above threshold conditions of H_s=2.5m

Spectral analysis of storm events

A further significant characteristic of the wave climate has been identified on the basis of measured wave data analysis; this is the spectral shape of the storm conditions. A high percentage of storm events at sites in the central English Channel are characterised by spectra with bi-modal wave periods and this has region-wide significance (Mason et al, 2008). Recent observations (2005-2009) suggest that more than 90% of all storm events above the 2.8m threshold used for Milford-on-Sea have been characterised by bimodal conditions (Figure 11).

This wave climate characteristic was not identified from the design wave hindcast, which provided a simple output of integrated parameters and generation of simple spectra. The design techniques used do not make provision for inclusion of such a variable and this characteristic was not considered to be a normal design variable at the design phase. The implication of this is examined further in conjunction with cross-shore beach response below.

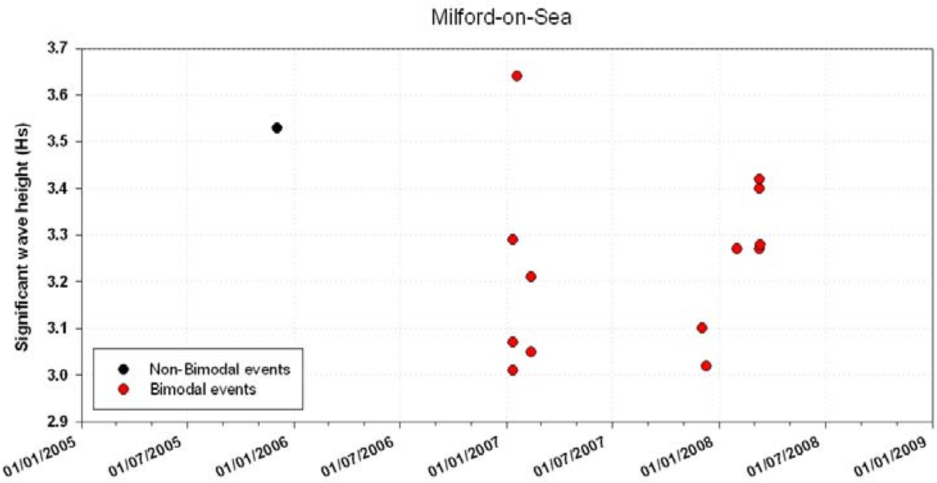

Figure 11 Temporal distribution of storm events with bimodal wave period characteristics for the period 2005-2009, based on threshold conditions of H_s=3.0m

Application of wave climate data in design phase

In common with most design investigations, the test wave conditions used in the design phase were based upon extrapolated extreme offshore wave heights transformed to nearshore locations, to examine overtopping, profile response and breaching. Similarly, transformed time-series of several years' data have been used as input to sediment transport models based on morphological averaged conditions.

All design methods used in development of the beach recharge design were based upon integrated wave parameters, although input to the physical modelling of beach design was based on wave conditions with a defined simple spectral shape.

Cross-shore response predicted by physical and numerical models

Design wave conditions, derived from synthetic hindcast wave data, have provided the basis for physical model testing of the cross-shore beach response. Test conditions were confined to events within the expected steepness parameter range 0.015 $>H_s/L_m$ >0.037; these are in-line with the suppositions provided by the synthetic wave model outputs. An extensive programme of tests was conducted in a 3-dimensional mobile-bed physical model. The primary purpose of the model was to determine the appropriate cross section of the recharge, to avoid overwashing in all but the most extreme conditions, and to identify critical conditions that could be used as a guide to inform the need for intervention during long-term management. A basic empirical framework was derived which identified the barrier geometry for critical overwashing threshold conditions (Bradbury, 2000). The extensive test programme provided an empirical framework relating the barrier inertia parameter (R_cB_a/H_s^3) to the wave steepness parameter (H_s/L_m) and with a derived overwashing threshold (Figure 12).

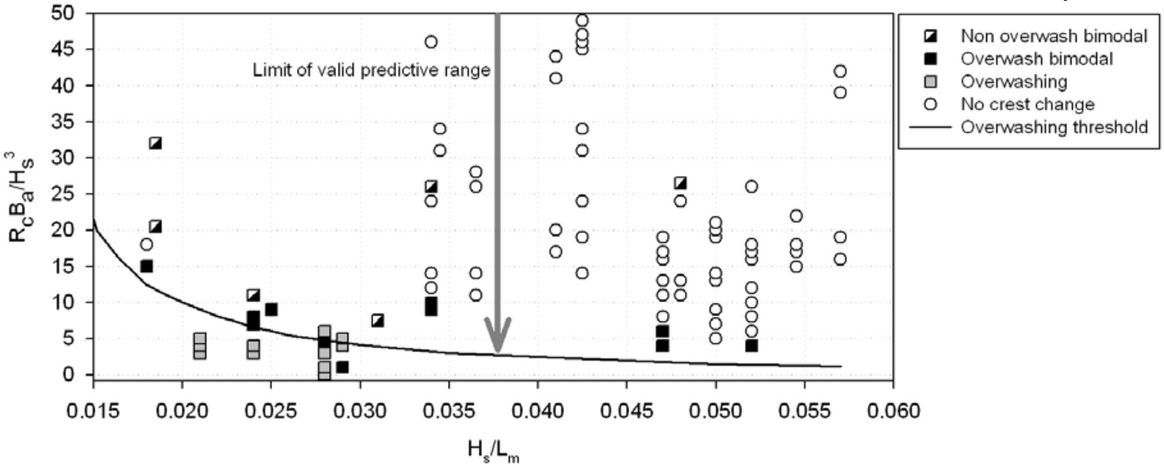

Figure 12 Comparisons between field measurements and the barrier inertia thresholds (from Bradbury et al 2009).

Longshore transport

Longshore transport calculations have been based on the use of extended time series (>15 years) of nearshore synthetic wave data within 1-line beach plan-shape models and empirical sediment transport formulae. These models are notoriously sensitive to wave conditions, in particular wave height and direction. Outputs assume that the wave climate and transport is representative of the future. Numerical modelling of wave climate at this site suggests that wave energy is variable along the length of the beach recharge and that there should consequently be a variable rate of longshore transport along the beach.

Differences between measured and modelled conditions

Observations have demonstrated considerable difference between the design wave climate and observations of the in service beach management scheme. A summary of variability between modelled and measured conditions is identified.

- Extreme wave conditions tested appear to have a return period of about 1:8 years rather than 1:100 years as required.
- A higher frequency of the more severe events used in testing has occurred than expected
- Wave climate statistics produced from field measurements since scheme implementation suggest that the design wave conditions derived from a 15 year hindcast are not representative of the characteristics of storm events from 1996-2008.
- Modelled wave conditions have generally been steeper than anticipated at the design stage.
- Many of the conditions tested have not occurred, because of the wave steepness difference.
- Bimodal conditions were not considered at the design stage but these have been shown to have more damaging impacts on beach profile response and breaching, relative to uni-modal conditions.
- Time series of synthetic wave climate data are characterised by higher than measured wave heights, for regularly occurring conditions (H_s<2m).
- The nearshore wave direction exhibits some considerable scatter when compared with measurements.

Implications of differences between measured and modelled conditions

- The implication of the differences between measured and modelled wave climate is that consistently steeper wave conditions have actually occurred than were expected. The combinations represented in the design phase physical model tests were based therefore on wave height and period combinations with longer wave periods than have actually occurred (Figure 12).
- The implication of the higher wave steepness is that lower wave run-up and potential for breaching might be expected, when the integrated parameters provide suitable design conditions.
- Most of the measured wave conditions lie outside of the valid range of the predictive framework for breaching; this reflects a future research need to extend the validity of the framework (Figure 12).
- Where wave conditions have occurred within the valid range, the predictive threshold seems to have worked fairly well, although there have been only a limited number of these conditions and few close to the theoretical threshold (Figure 12).
- The field data has provided the opportunity to populate the breach prediction data-set with steeper wave conditions than tested. Consequently, an approximation of the threshold can be determined for this site for conditions where $H_s/L_m>0.037$. The vast majority of the data has resulted in conditions where overwashing has not occurred. Much of the field data for the steeper wave conditions lies well above the threshold condition (Figure 12).
- The field data provides a valuable extension to the model based framework. The fact that the beach has been maintained at a healthy level has enabled a range of safe conditions to be added to the predictive framework.
- Despite the fact that the beach has remained in good condition, overwashing has occurred on a number of occasions; this has occurred in surprising circumstances relative to the morphodynamic and design expectations. Detailed examination of wave climate conditions associated with these events has identified that the wave conditions were characterised by bi-modal spectra on each occasion and that a significant proportion of the energy component (20-40%) has typically been in the swell energy range of frequencies.
- Cross-shore profile responses are not well described in bi-modal wave period conditions, which occur regularly. The models generally under-predict wave run-up and crest cut back in such conditions, when simple integrated wave parameters (H_s, T_m) are used. Whilst these observations are not conclusive, it is suggested that spectral shape is a key variable that is not normally considered in the design process. (Figure 12)
- The response of the beach under these conditions appears to be worse than conditions defined by spectra with simple shapes. This is consistent with other laboratory observations of profile response (Coates et al, 1998). Current design guidance does not provide an obvious means of dealing with this design variable, apart from site specific physical model testing.
- Longshore transport calculations conducted at the design stage suggested faster transport rates than have actually occurred since construction. On average the actual longshore transport rates (1998-2008) have been about 45% of the initial predictions suggested by the modelling (estimated at circa. 16,000m^3 per year). Although the observed changes are about 45% of the model predictions, this might be considered a reasonable result relative to realistic modelling expectations.
- The fact that longshore transport calculations are energy based must be considered. Post construction measurements of wave conditions suggest that severe storm conditions have been generally rougher than those suggested at the design stage. This is partially countered by the observation that the wave model overpredicts wave heights for conditions where H_s<2m. Subsequent sample runs of one year of

measured and modelled time series within a beach plan shape model, suggest that use of the measured data reduces the drift potential to about 60% of that provided by the modelled wave data (about 9,000m^3 per year). This observation suggests that the modelling of sediment transport rates may perhaps be more reliable when using measured data. Sensitivity tests conducted in numerical modelling suggested that a mean change of +/-2^O in alignment might result in an annual difference in transport of about +/-4000m^3 at this site; this variable has not been examined in context with field measurements in this investigation.

Whilst the measured wave conditions have been somewhat different to those expected, the beach has performed generally better than predicted (Figure 13). Where conditions have been characterised by similar conditions to those developed in the physical model based empirical frameworks, results have been comparable. The implications of differences in wave climate observations suggest that lower run-up might be expected under most conditions, since the wave period appears to have been overpredicted. This implies that the as constructed crest might be higher than is optimal. This is countered however by the impact of bi-modal conditions, which result in higher wave run-up.

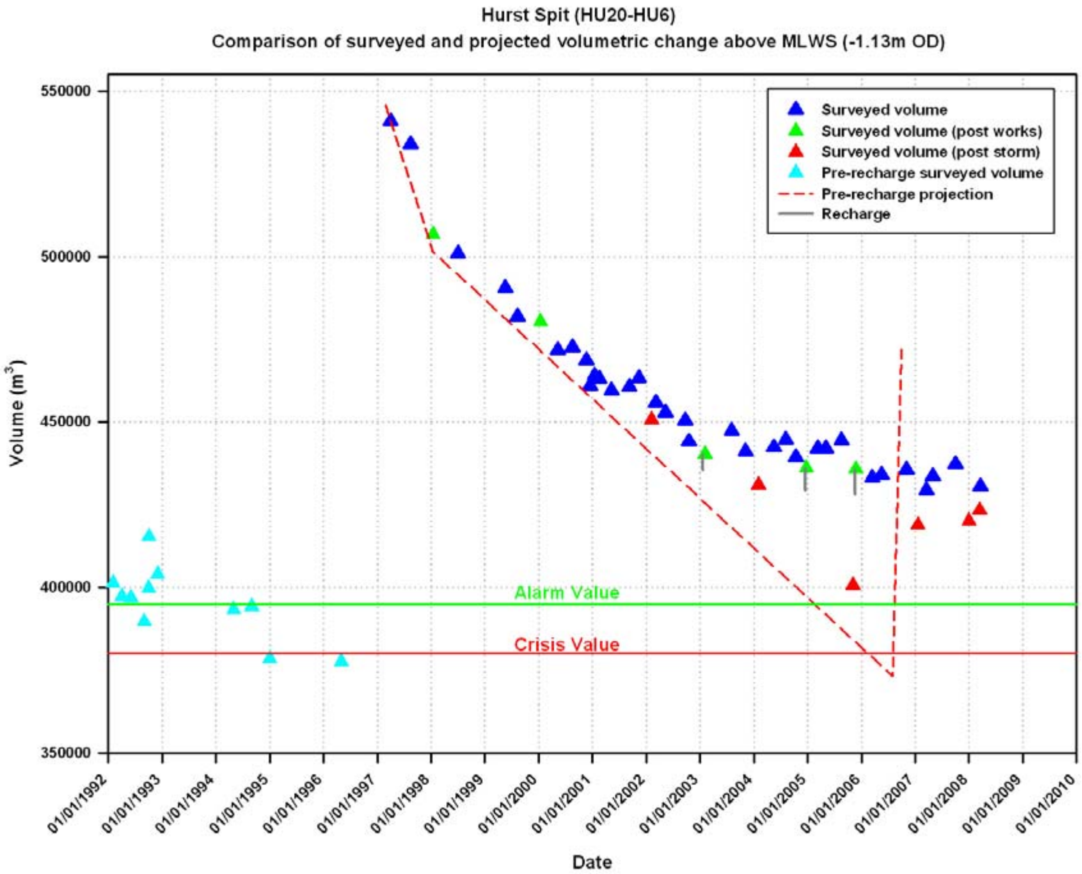

Figure 13 Lifecycle performance of beach recharge at Hurst Spit (from Bradbury et al 2009)

Conclusions

Wave climate statistics produced from field measurements since scheme implementation suggest that the modelled design wave climate has not provided a representative guide to the characteristics of storm events from 1996-2008. Significant differences in wave climate characteristics are evident between modelled and measured wave conditions. Evidence suggests that:

Wave climate

- The offshore wave conditions have been more severe than the 1974-1990 design hindcast would suggest.
- The offshore design 1:100 year significant wave height has been recalculated on the basis of observations since 1990.
- The design significant wave height has been exceeded on numerous occasions since 1996. This reflects both modelling techniques, and also the sample period used to derive the wave climate.
- Wave period data is widely scattered, but the measured wave periods are typically about 20% lower than models indicate.
- Wave steepness is subsequently greater than models suggest in extreme conditions. Many of the test conditions used at the design stage have been inappropriate therefore.
- A high frequency (>90%) of recent storm events are represented by wave conditions with bi-modal (period) characteristics.
    - These trends are observed on a region wide basis, and have significant implications for design and management.
- Wave conditions since scheme implementation have not been generally representative of those modelled at the design stage. Whilst the measured wave conditions have been somewhat different to those expected, the beach has performed better than predicted.

Implications of wave climate variability on scheme performance

Wide ranging observations have demonstrated some significant differences between monitored wave climate conditions and predictions at the design phase; these have beach management performance implications. Many of the differences in performance are interlinked. Overall the scheme has performed better than predicted, despite conditions being significantly more severe than anticipated at the design phase. Best practice design methods have been adopted consistently. In this instance the under and over design elements seem to have cancelled each other out; this is attributed to good luck rather than adequate science.

The monitoring has had a major impact on management of the beach system. It has demonstrated clear differences by comparison with modelled expectations and has provided the basis for modification of maintenance and long term planning requirements. The monitoring has been particularly valuable for the purposes of evaluation of threshold damage levels and for long term planning of interim recharge requirements. Monitoring has identified a need for a general review of the scheme standard of service and the need to redefine design conditions by reference to bi-modal wave conditions

- Overall, performance of the beach recharge scheme has been comparable with initial expectations.
- Sediment transport rates have been lower than predicted by numerical models.
    - Measured wave data provides more reliable sediment transport results than synthetic wave data.

- Overwashing and wave run-up is under-predicted by the empirical breach prediction model in bi-modal wave conditions.

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Keywords

Wave climate, beach response modelling, coastal monitoring