APPENDIX D: The STORM Model

D1. Introduction

The JERICHO project aims to analyse measured buoy data and compare it with wave heights and periods derived from satellite data. The analysis is intended to describe the wave climate and identify any long-term trends.

Halcrow s role in the project, in combination with Proudman Oceanographic Laboratories (POL), was to determine whether changes in deep water wave climate would have a commensurate effect on the wave climate experienced at the coast. The investigation was based on using numerical models to transfer the deep water wave climate to the shore.

D2. The STORM Model

Halcrow's spectral wave transformation model, based on ray tracing, (REFPRO and SANDS) has been used for wave transformation from offshore to inshore. At offshore, apart from the integrated parameters, (H_s- significant wave height, T_p- peak period, θ_m- mean direction), there is also a full frequency spectrum and information on the mean direction and spreading. As the frequency spectra were well-represented by the JONSWAP spectrum, proposed by Hasselman et al (1973), the integrated parameters derived from the measurements were used to specify an analytical form for the directional spectrum. The description of the offshore directional spectrum, S(θ,f), is completed by defining the directional spreading function, G(θ,f), such that

$$S(\theta, f) = E(f)G(\theta, f)$$

where E(f) is the JONSWAP frequency spectrum and G is given by a cosine power law with Mitsuyasu corrections:

$$G(\theta, f) = \frac{1}{2\sqrt{\pi}} \frac{\Gamma(s+1)}{\Gamma(s+1/2)} \cos^{2s}((\theta - \bar{\theta})/2)$$

where

$$|\theta - \bar{\theta}| < \pi \qquad s = s_m \left(\frac{f}{f_p} \right)^{\mu} \qquad s_m = 9.77$$

and

$$\mu = \begin{Bmatrix} -2.33 & for & f \ge f_p \\ 4.06 & for & f < f_p \end{Bmatrix}$$

and Γ(x) is the gamma function (see e.g. Gradshteyn & Ryzhik 1980).

Abernethy & Gilbert (1974) showed that the inshore directional spectrum, S(ϕ,f), may be determined from:

$$S(\phi, f) = \frac{c_o c_{go}}{c c_g} S_o(\theta, f)$$

where c and c_o are respectively the wave phase velocity inshore and offshore, and c_g and c_{go} are the wave group velocity inshore and offshore. Under the assumption of Airy wave behaviour the phase velocity and group velocity are related by

$$c_g = \frac{1}{2}c(1+\frac{y}{\sinh(y)}) \qquad with \qquad y = \frac{4\pi h}{L}$$

where h is the water depth and L is the wave length.

Having defined a discretisation of the variables f and ϕ, a ray path can be calculated for each discrete frequency-inshore direction pair, backtracking from the inshore location out to deep water, and so obtaining the corresponding value of θ. Repeating this for each f-ϕ pair, the inshore spectrum can be constructed once the appropriate phase and group velocities have been calculated. The spectrum calculated in this way is termed unsaturated as no account of wave energy dissipation has been made.

Bouws et al. (1985) proposed a model for water wave spectra in finite depth water, (the TMA spectrum). This spectrum accounted for shallow water effects such as wave-wave interaction, wave breaking and dissipation of wave energy due to the existence of a bottom boundary layer. The TMA spectrum may be interpreted as providing an upper bound on the energy at any particular frequency. The saturated inshore spectrum is obtained by taking the minimum of the spectrum as calculated via backtracking and the TMA spectrum for each frequency.

The ray tracing program calculates the paths of wave rays (lines orthogonal to the wave crests) as the wave propagates from element to element across the bathymetric model, using a circular arc technique. This may be done for specific tide levels and ranges of wave periods, tracking to or from a number of study points.

Back-tracking rays are normally calculated for three water levels. For each water level rays were calculated for a set of fifteen periods, (2.0, 2.3, 2.7, 3.2, 3.7, 4.4, 5.1, 6., 7.0, 8.2, 9.6, 11.2, 13.1, 15.5 & 18.0 seconds), covering a clockwise directional range from 330°N to 150°N.

Time series of integrated wave parameters are thus generated from the following procedure:

- Construct an analytical form for the deep water directional spectrum from the integrated wave parameters derived from the measurements;
- Estimate total water depth at inshore point as the sum of the mean depth and predicted tide level;
- Transform this spectrum to the inshore point using the pre-computed refraction results (linearly interpolating over period, direction and water depth as necessary);
- Compute the saturated inshore spectrum;
- Calculate the inshore integrated wave parameters from the saturated inshore spectrum;
- Repeat above for each point in the time series of offshore wave data.

D3. Using the STORM Model

In order to calculate wave refraction patterns, a digital model of the seabed is required for a sufficient distance around the point of interest. The area that must be covered depends on the topography of the site, the wavelength of the longest waves to be refracted, the type of refraction study (forward or backward tracking). The model boundaries will be defined by:

(a) The shoreline.

(b) The depth contour at which the water depth is half of the longest wavelength used.

(c) The edges of any areas from which waves cannot reach the area of interest.

In many cases these criteria will delineate a small area of seabed which can be readily modelled. In some cases, however, shallow water will extend some kilometres from the shore, making the second limit above unrealistic. In these cases, the seaward boundary must be based on some other criterion. Often this problem is caused by a wide, shallow shelf, such that in the offshore direction the water depth increases quite rapidly to, say, thirty metres, then remains at this depth for many kilometres before reaching deeper water or another coast. It is reasonable in these circumstances to model only the nearshore slope and any nearshore shoals, as the refraction approximations will break down at great distances from the shore. Where the offshore depths do, eventually, increase to a suitable deep water' value, the refraction programs can be set to recognise this without requiring the seabed model to extend to deep water, so long as the seabed beyond the offshore boundary of the model can be approximated by a sloping plane. This is usually the case.

Once the limits of the model have been determined, suitable scales must be set for the grid meshes at whose nodal points the depths are defined. The magnitude of changes due to refraction is greatest in shallow water. To make use of this fact, and economise on the size of the seabed model, a closely spaced mesh of depth values is used in shallow water, particularly around the area of interest, and more widely spaced meshes are used in deeper water. In the finest grid mesh, the spacing of the depth values should be around one wavelength if the topography is complex, or up to five wavelengths for a simple, e.g. plane, seabed. At the outer edges of the study area the spacing may be ten, twenty or even fifty wavelengths, again depending on the topography. As a rule of thumb, the spacing should be similar to the spacing of spot depths or contours on an Admiralty chart of the area.

The Storm model calculates the paths of wave rays (lines orthogonal to the wave crests) as the wave propagates from element to element across the bathymetric model, using a circular arc technique. This may be done for specific tide levels and ranges of wave periods, tracking to or from a number of study points.

The program may be used in two modes,

Æ forward tracking

Æ backward tracking

Forward tracking provides a general view of wave conditions over a wide area. A monochromatic, unidirectional wave train is propagated from deep water towards the shoreline from a series of offshore points.

Backward tracking provides a more accurate and detailed study of the wave climate and is the basis of wave height and energy determination. The waves are tracked in a range of directions from a study point.

D4. Application of STORM for JERICHO Project

Halcrow has used the Storm model to transfer the deep water wave climate to the shore to determine whether changes in deep water wave climate will have any effect on the wave climate experienced at the coast. We have considered three sites Holderness, Camarthen Bay and Lyme Bay (West Bexington).

D5. Analysis at Holderness

The wave modelling and analysis at Holderness has involved the following:

- Setup of Halcrow s model STORM;
- Setup Halcrow s Shoreline And Nearshore Data System (SANDS);
- Transformation and comparison of wave data.

D5.1. Wave data

POL have supplied Halcrow with measured time series wave data and in return Halcrow have supplied POL with bathymetry data required to transform the deep ocean waves to within 10km of the coast. The data supplied from POL is recorded from their wave rider buoys and is to Ordnance datum. Satellite time series wave data has been provided by Satellite Observing Systems, due to the nature of the satellite the data is very sparse, approximately one record every ten days. Details of the time series wave data provided by are shown in Tables 1 to 2.

Table 1 Holderness wave and depth time series data.

Location	Mean recorded depth (m)	Type of buoy	Start of data	End of data
N1	12.5	Wave Rider (WR)	09/10/94	16/01/96
N1b	12.5	POL Monitoring Platform (PMP)	09/10/94	29/12/95
N2	18.3	Directional Wave Rider (DWR)	08/11/94	16/01/96
N3	29.9	Directional Wave Rider (DWR)	14/10/94	28/02/95
N3	N/A Satellite data	N/A Satellite data	07/10/92	24/12/97

Note: Location N1b is bottom-mounted device measuring Pressure and current data.

Table 2 Positions of Holderness study locations.

Location	Latitude (N)	Longitude (E)	Easting	Northing
N1	053,45.84	000,00.77	532661	431630
N1b	053,45.83	000,00.49	532350	431622
N2	053,47.51	000,03.34	535390	434832
N3	053,50.57	000,09.11	541566	440674

D5.2. ***Bathymetric data***

The Holderness study area is covered by admiralty charts 107 and 121.

These charts have been previously digitised by Halcrow, and were therefore retrieved from Halcrow s data archive system. The data is held as Eastings, Northings and depth values on a Geographical Information System (GIS) system, Microstation.

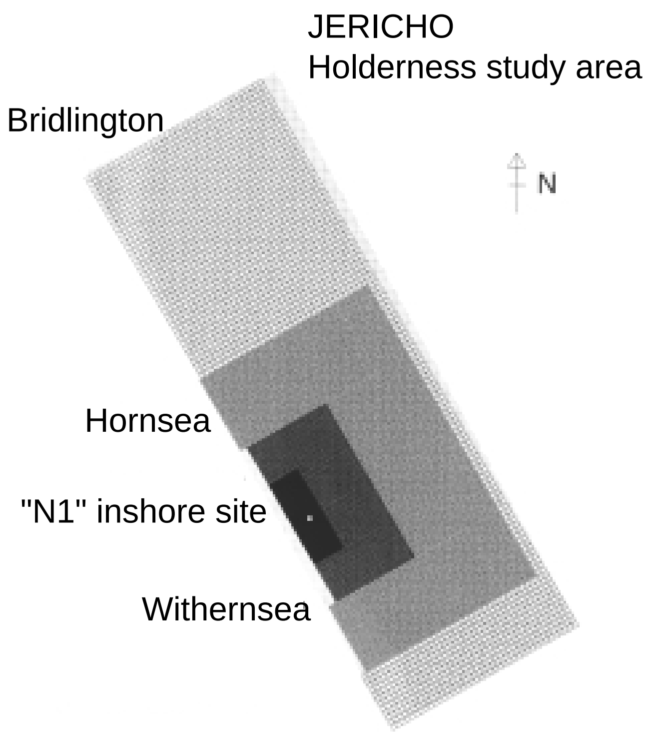
D5.3. Wave Modelling

The program calculates the paths of wave rays (lines orthogonal to the wave crests) as the wave propagates from element to element across the bathymetric model, using a circular arc technique. This may be done for specific tide levels and ranges of wave periods, tracking to or from a number of study points.

For this study we have used backward tracking, this provides an accurate and detailed study of the wave climate and is the basis of wave height and energy determination. The waves are tracked in a range of directions from study point.

Our objective was to transform both recorded and satellite waves from location N3 to positions N1 and N2 then compare the actual recorded waves at N1 and N2 with the transformed waves.

The REFPRO grids were set up over the Holderness bathymetry using Halcrow s program GRIDMKR (Gridmaker). The grid system extends 19km offshore and 60km along the coast approximately, starting with a 50m grid over the study location area, then gradually increasing offshore from 100m to 200m and finally 500m. The refraction grid structure can been seen in Figure 1.



- Figure 1 STORM model grid for Holderness

Halcrow s program GRIDMKR was then run in order to produce the refraction grids. GRIDMKR interpolates data points and converts them into a bathymetric grid, suitable for use with the REFPRO model.

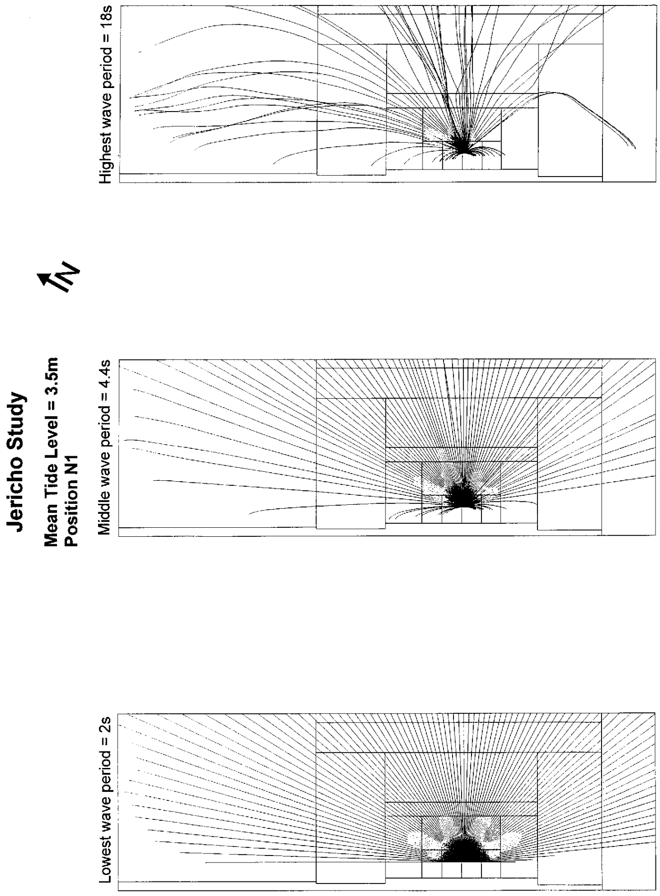


Figure 2 Example of ray paths for the STORM model for three different wave periods at one water level

REFPRO was setup and ran for locations N1 and N2 . The model was run for three water levels namely 1.1m (MLWS), 3.55m (mean of all tide levels) and 6.1m, (MHWS), these were derived from the Bridlington tide gauge, shown in Table 3. The wave periods used for REFPRO are a standard set of fifteen, the scan range for the rays start from 330 degrees and go clockwise around to 150 degrees, shown in Table 4.

Table 3 Tidal Levels at Bridlington referred to Chart Datum.

Place	Heights in metres above datum				Datum
	MHWS	MHWN	MLWN	MLWS	
Bridlington	6.1	4.7	2.3	1.1	3.35 below ODN

Table 4 REFPRO conditions for locations N1 and N2 .

Wave period (s)	Scan range from (deg)	Scan range to (deg)
2.0	330	150
2.3	330	150
2.7	330	150
3.2	330	150
3.7	330	150
4.4	330	150
5.1	330	150
6.0	330	150
7.0	330	150
8.2	330	150
9.6	330	150
11.2	330	150
13.1	330	150
15.5	330	150
18.0	330	150

After running REFPRO the results are checked by using REFPLT this program enables the backtracking rays to be plotted, examples of this are shown in Figure 2.

The refraction coefficients calculated by REFPRO were then imported into SANDS where the wave transformations were to take place.

D5.4. Wave Data Analysis

Halcrow's Shoreline and Nearshore Data System, SANDS, is a software package for the storage, retrieval and analysis of coastal and environmental data. The system combines mapping and graphing with various data entry and analysis functions, including some sophisticated modelling.

A SANDS database was setup specifically for the JERICHO project.

The locations provided from POL (shown in Table 2) were entered into SANDS along with the relevant converted time series wave data. A tide point is required to do wave transformations within SANDS and Spurn Head was chosen because it was nearest to the study locations, the tidal constituents from the 1998 Admiralty tide tables were entered into SANDS, therefore providing a predicted tide.

Both recorded and satellite time series wave data was then transformed from location N3 to N1 and N2 .

SANDS was then used to graph the recorded wave data at locations N1 and N2 .

Periods of interest were then printed out together with the corresponding periods from the transformed data, for comparison.

Direct comparison of wave data at position N1 showed that transformed wave heights are very close to the measured ones. For the important storm period of 31/12/1994 to 07/01/1995 and 07/02/1995 to 14/02/1995, the transformed wave heights follow the measured wave height very closely. It demonstrates that the STORM model performs very well for site Holderness over storm periods.

This method of comparison via graphing is not suitable for displaying the recorded and transformed satellite data. The satellite only passes over the site N3 every ten days

therefore the data is very sparse, this means that there are only fourteen common records that can be compared directly between the recorded and satellite data sets.
The recorded and transformed satellite data is therefore best compared by means of an extremes analysis.
Inshore wave data were sent to SOS for extreme analysis (see e.g. JTR-27)..

D6. ANALYSIS AT CARMARTHEN BAY

D6.1. Wave data

Satellite Observing Systems have supplied Halcrow with measured time series wave data.
The data supplied is from a Met. Office wave recording buoy situated near St Gowan, in Carmarthen Bay. The wave data comprises of height, period (zero crossing) and direction, one record per hour is recorded, although occasionally records are missing.
Also Southampton Oceanography Centre provided JERICHO with measured data from a short term project called SWALES . This data also comprises of height, period (zero crossing) and direction, one record every half hour is recorded, although occasionally records are missing.
Details of the time series wave data provided by are shown in Tables 5 and 6.

Table 5 Carmarthen Bay wave time series data.

Location	Mean recorded depth (m)	Type of buoy	Start of data	End of data
St Gowan	Unknown	Wave Rider (WR)	02/09/94	31/12/97
SWALES	Unknown	Wave Rider (WR)	20/10/92	30/12/93

Table 6 Position of Carmarthen Bay *in situ* data.

Location	Latitude (N)	Longitude(W)	Easting	Northing
St Gowan	51.50	-4.90	198742	181937
SWALES	51.582	-4.784	207138	190741

D6.2. Bathymetric data

The Carmarthen Bay study area is covered by admiralty chart 1076.
This chart has been previously digitised by Halcrow, and was therefore retrieved from Halcrow s data archive system. The data is held as Eastings, Northings and depth values on a Geographical Information System (GIS) system, Microstation.

D6.3. Wave Modelling

Our objective was to transform recorded waves from the offshore position at St Gowan and Swales to the inshore points at Amroth and Worms Head. These locations were decided upon after discussions between all organisations involved with the Jericho project. It was decided to choose one point at a sheltered position, Amroth and the other at an exposed position, Worms Head. The positions decided upon and used for REFPRO are shown in table 7.

Table 7 Position of Inshore Carmarthen Bay study locations.

Location	Depth in model (m)	Easting	Northing
Amroth	1.09	216597	206401
Worms Head	30.43	238240	186090

The REFPRO grids were set up over the Carmarthen Bay bathymetry using Halcrow s program GRIDMKR (Gridmaker). The grid system extends 40km offshore and 60km alongshore with a 150m grid over the study location area, then gradually increasing offshore from 300m and finally 600 m.
REFPRO was setup and ran for locations Amroth and Worms Head . The model was ran for three water levels namely 1.1m (MLWS), 4.825m (mean of all tide levels) and 8.6m, (MHWS), these were derived from the Burry Port tide gauge, shown in Table 8. The wave periods used for REFPRO are a standard set of fifteen, the scan range for the rays start from 90 degrees and go clockwise around to 300 degrees, shown in Table 9.

Table 8 Tidal Levels at Burry Port referred to Chart Datum.

Place	Heights in metres above datum				Datum
	MHWS	MHWN	MLWN	MLWS	
Burry Port	8.6	6.6	2.3	1.1	4.70 below ODN

Table 9 REFPRO conditions for locations Amroth and Worms Head .

Wave period (s)	Scan range from (deg)	Scan range to (deg)
2.0	090	300
2.3	090	300
2.7	090	300
3.2	090	300
3.7	090	300
4.4	090	300
5.1	090	300
6.0	090	300
7.0	090	300
8.2	090	300
9.6	090	300
11.2	090	300
13.1	090	300
15.5	090	300
18.0	090	300

The refraction coefficients calculated by REFPRO were then imported into SANDS where the wave transformations were to take place.

D6.4. Wave Data Analysis

The wave locations were entered into SANDS along with the relevant converted time series wave data. The depths of the study locations were corrected from Chart datum to Ordnance datum by a conversion of —4.70 metres, before importing into SANDS.
The refraction coefficients calculated by REFPRO were also imported into SANDS to the relevant locations, Amroth and Worms Head .

A tide point is required to do wave transformations within SANDS and Burry Port Head was chosen because it was near to the study locations, the tidal constituents from the 1998 Admiralty tide tables were entered into SANDS, therefore providing a predicted tide.
Recorded time series wave data was then transformed from St Gowan to Amroth and Worms Head . Next recorded time series wave data was transformed from SWALES to Amroth and Worms Head . SANDS was then used to graph the recorded and transformed wave data.
Inshore wave data were sent to SOS for extreme analysis.

D7. ANALYSIS AT LYME BAY

D7.1. Wave data

Proudman Oceanographic Laboratories have supplied Halcrow with measured time series wave data. The data supplied comprises of two offshore points in Lyme Bay, which have been combined two produce one data set. The wave data comprises of height, period (zero crossing) and direction, one record for every ten days approximately, although occasionally records are missing and there is no data from August 1994 to January 1997.
Details of the time series wave data are shown in Tables 10 and 11.

Table 10 Lyme Bay wave time series data.

Location	Mean recorded depth (m)	Type of buoy	Start of data	End of data
Lyme Bay	Unknown	Unknown	25/09/92	22/12/97

Table 11 Position of Lyme Bay study location.

Location	Latitude (N)	Longitude(W)	Easting	Northing
Lyme Bay	50.55	-2.92	334828	072719

D7.2. ***Bathymetric data***

The Lyme Bay study area is covered by admiralty chart 3315.
This chart has been previously digitised by Halcrow, and was therefore retrieved from Halcrow s data archive system. The data is held as Eastings, Northings and depth values on a Geographical Information System (GIS) system, Microstation.

D7.3. Wave Modelling

Positions near to the shore were chosen. It was decided to choose one point to the east of the tide level station at Lyme Regis near Bridport and another position to the west of Lyme Regis near Seaton. The positions decided upon and used for REFPRO are shown in table 12 below.

Table 12 Positions of Lyme Bay inshore locations.

Location	Depth in model (m)	Easting	Northing
Location 1	3.00	216597	206401
Location 2	2.00	238240	186090

The REFPRO grids were set up over the Lyme Bay bathymetry using Halcrow s program GRIDMKR (Gridmaker). The grids extends 20km offshore and 60km alongshore approximately the grids start with a 200m grid over the study location area, then increase to 400 m..
REFPRO was setup and ran for locations 1 and 2 . The model was ran for three water levels namely 0.6m (MLWS), 2.425m (mean of all tide levels) and 4.3m, (MHWS), these were derived from the Lyme Regis tide gauge, shown in Table 13. The wave periods used for REFPRO are a standard set of fifteen, the scan range for the rays start from 90 degrees and go clockwise around to 270 degrees, shown in Table 14.

Table 13 Tidal Levels at Lyme Regis referred to Chart Datum.

Place	Heights in metres above datum				Datum
	MHWS	MHWN	MLWN	MLWS	
Lyme Regis	4.3	3.1	1.7	0.6	3.22 below ODN

After running REFPRO the results are checked by using REFPLT this program enables the backtracking rays to be plotted, examples of this are shown in Figure 2.
The refraction coefficients calculated by REFPRO were then imported into SANDS where the wave transformations were to take place.

Table 14 REFPRO conditions for locations 1 and 2 .

Wave period (s)	Scan range from (deg)	Scan range to (deg)
2.0	090	270
2.3	090	270
2.7	090	270
3.2	090	270
3.7	090	270
4.4	090	270
5.1	090	270
6.0	090	270
7.0	090	270
8.2	090	270
9.6	090	270
11.2	090	270
13.1	090	270
15.5	090	270
18.0	090	270

D7.3.1. Wave Data Analysis

The wave locations were entered into SANDS along with the relevant converted time series wave data. The depths of the study locations were corrected from Chart datum to Ordnance datum by a conversion of —3.22metres, before importing into SANDS. The refraction coefficients calculated by REFPRO were also imported into SANDS to the relevant locations, 1 and 2 . A tide point is required to do wave transformations within SANDS and Lyme Regis was chosen because it was near to the study locations, the tidal constituents from the 1998 Admiralty tide tables were entered into SANDS, therefore

providing a predicted tide. Recorded time series wave data was then transformed from Lyme Bay to positions 1 and 2 .
Inshore wave data were sent to POL for their comparison, and were sent to SOS for extreme analysis.

D8. Potential Benefit Of Using Satellite Wave Data

Wave heights can be derived routinely from satellite altimeter data. Suitable satellite coverage of the coastal waters of the UK now cover a period of approximately 10 years. The recovery of wave heights from satellite observations is very useful to areas greater than approximately 10km from the coastline. Thus, to be of direct use to coastal engineers these relatively deepwater wave conditions have to be transformed to the sites of specific interest with help of a numerical wave model.
Results of an investigation into whether the archive of satellite data can provide a useful source of wave information for providing the design wave climate for coastal works have been presented in this report. In situ wave measurements in deep, intermediate and shallow water at sites Holderness, Lyme Bay (West Bexington) and Camarthen Bay have been used to assess the accuracy of satellite-derived and wave conditions in deep water, and shallow water conditions predicted using a numerical wave transformation model. The results reveal that the satellite wave data can be used for coastal engineering, provided that wave directions are obtained from somewhere else.

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