Overstrand to Walcott Strategy Study

Hydrodynamics

Part II: Technical Support Information

Report EX 4692
December 2002

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HR Wallingford

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This report describes work commissioned by North Norfolk District Council whose representative was Mr Peter Frew. The HR Wallingford job numbers were CDR3212 and CDR3214. The work was carried out by members of the Engineering Systems and Management Group and the Coastal and Seabed Processes Group at HR Wallingford. The HR Wallingford project manager was Mr Paul Sayers.

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Summary

Overstrand to Walcott Strategy Study

Hydrodynamics

Part II: Technical Support Information

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This report addresses the sea conditions required within the Overstrand to Mundesley and the Mundesley to Walcott strategy studies. Existing information on waves, tidal levels and tidal currents was collated, wave and tidal models were established and run, and results are presented for a number of locations within the two study areas.

These results provide the hydraulic loading conditions needed for calculations performed elsewhere within the strategy study, in terms of:

- tables and roses of wave climate and extremes;
- tables of extreme sea levels;
- maps and tables of tidal currents;
- tables of extreme combinations of waves and water levels;
- long-term wave and water level time series required for cliff modelling.

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1. INTRODUCTION

This report is concerned with the hydraulic loading that changes the shoreline, namely the waves, tidal currents, and tidal levels. An accurate estimate of these processes is an important factor both in quantifying beach and cliff behaviour and in assessing the types of coastal management or defence scheme that may be feasible.

Current data were obtained from published sources and from the tidal flow model used during this study. Results were produced through the tide throughout the two strategy study areas and further offshore. Illustrative results are given in this report as maps of tidal currents at particular states of the tide, and tabulations and plots through the tide for particular locations.

A wave model was set up for the area, and predictions were made for one offshore and ten nearshore locations in the study area. Illustrative results are provided for the following four locations: Overstrand, Trimingham, Mundesley, and Bacton.

Tidal range data, extreme sea level predictions, and information on future sea level rise were collated from several published sources, including Admiralty tide tables. Tables of joint probability extremes of waves and water levels were also produced for the four locations.

Results in addition to those shown in this report were made available for other calculations elsewhere in the two studies as necessary.

2. TIDAL LEVELS

The tidal level at any instant in time will be the summation of an ‘astronomical’ tidal level and a ‘residual’ level caused by meteorological effects. While astronomical tidal level is accurately forecasted in published tide tables, the residual components (i.e. atmospheric pressure, winds, and temperature) are not easily predicted. In summer, the ‘residuals’ are usually small and so the predicted tidal levels are usually close to those observed. In winter, however, deep atmospheric depressions and strong winds can radically alter the propagation of the tides. The most important effect occurs when a ‘storm surge’ is created. A storm surge is a wave-like disturbance of the sea surface that typically travels southwards down the North Sea increasing in amplitude as it travels into the narrower area between East Anglia and the European mainland. If a large storm surge coincides with a high astronomical tidal level, then the resulting ‘total’ water level can cause great problems to coastal defences, and occasionally leads to disastrous flooding of low-lying areas, for example in 1953 and 1978. This chapter therefore considers both the astronomical tides and the residuals / surges, before deriving estimates of exceptional high total water levels, with contributions from both.

2.1 Astronomical tides

The propagation of tides in the southern North Sea, and hence along the coastline of North Norfolk, is far from straightforward. Put simply, the tide off the East Anglian coastline travels as an anti-clockwise gyre or eddy centred close to Great Yarmouth. The rise and fall of the tide is small close to the centre of this gyre, increasing further from the centre. Hence, on a mean spring tide at Great Yarmouth or Lowestoft, the vertical difference between high and low water level (the tidal range), is only 1.9m, increasing to 6.5m at Hunstanton (see Figure 2.1). At Cromer, the mean spring tide range is about 4.4m, decreasing slightly moving southward through the study area.

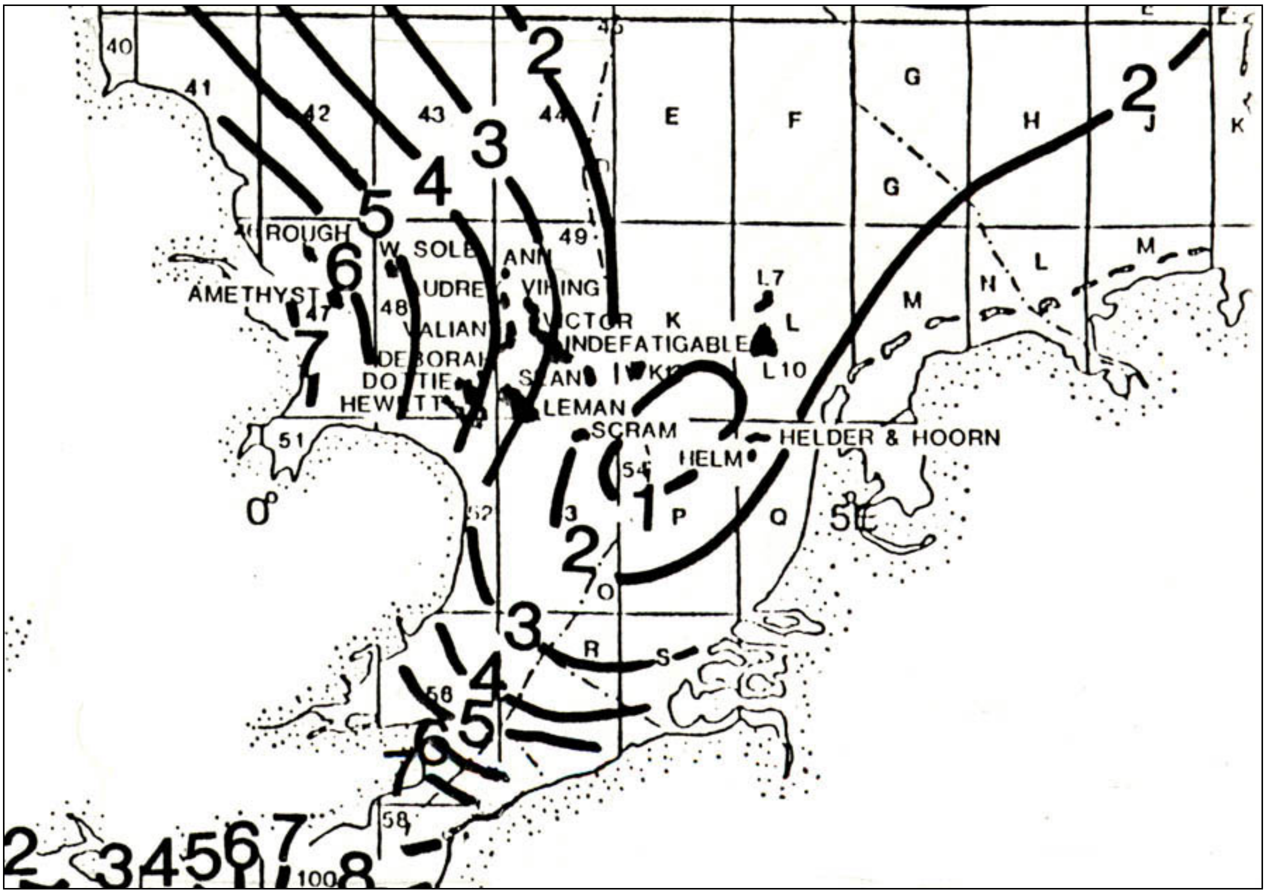

Figure 2.1 Tidal level variation off the East Anglian coastline (MHWS in mCD)

The variations in tidal levels at Cromer are particularly well understood because of the presence of an A-Class tidal gauge on the Pier. To the nearest 0.10m, the normal astronomical tidal levels (i.e. unaffected by atmospheric effects) are as follows:

		mCD	mODN
Mean High Water Springs	(MHWS)	5.2	2.45
Mean High Water Neaps	(MHWN)	4.1	1.35
Mean Sea Level	(MSL)	2.8	0.05
Mean Low Water Neaps	(MLWN)	2.1	-0.65
Mean Low Water Springs	(MLWS)	0.8	-1.95

Levels in the first column above are given relative to Admiralty Chart Datum at Cromer, which is set 2.75m below Ordnance Datum Newlyn (ODN).

Corresponding figures for Winterton, the next position south of Cromer for which values are given in the Admiralty Tide Tables, are:

	mCD	mODN
MHWS	3.2	1.38
MHWN	2.6	0.78
MSL	1.81	-0.01
MLWN	1.2	-0.62
MLWS	0.6	-1.22

Overstrand lies about one twelfth of the distance between Cromer and Winterton, Trimingham about one sixth, Mundesley about two sevenths, and Bacton about three sevenths of the distance. Tidal range data were therefore interpolated as follows:

	Overstrand mODN	Trimingham mODN	Mundesley mODN	Bacton mODN
MHWS	2.36	2.27	2.14	1.99
MHWN	1.30	1.25	1.19	1.11
MSL	0.05	0.05	0.03	0.02
MLWN	-0.65	-0.65	-0.64	-0.64
MLWS	-1.89	-1.83	-1.74	-1.64

2.2 Surges and residuals

North Sea surges have been studied by a variety of authors (Hunt 1972, Keers 1966, and Corkan 1948). Some of this work is briefly summarised here.

North Sea surges tend to originate off the north-west coast of Scotland, and propagate into the North Sea in the form of a progressive long wave. Coriolis force guides the surges southwards down the eastern coast of the UK and around the North Sea in an anticlockwise direction. The speed of propagation of the surge is similar to that of the astronomical tidal wave.

The meteorological conditions that produce surges in the North Sea are varied. The most severe surges are generally of the type described below.

Large low-pressure systems tracking north-eastwards from the Atlantic Ocean, between Iceland and the British Isles, generate strong south westerly winds. These winds cause a small positive surge on the north-west coast of Scotland, as water 'piles up', and a small negative surge on the east coast of the UK, as water is pushed towards Norway.

As the depressions move further north-eastwards, the wind veers and starts to blow from the north. These northerly winds further enhance the surge, which by now will have propagated across the north coast of Scotland and into the north-west North Sea. This surge travels down the eastern coast of Britain being constantly reinforced by strong northerly winds, and reaches a maximum in the south western corner of the North Sea (see Figure 2.2). In the study area, the maximum surge elevation expected once in 50 years is between 2.50 and 2.75m.

As surges propagate into the shallower water in the southern North Sea, surge tide interaction can become a prominent feature. That is to say the extent of the surge can be amplified or restricted depending on the astronomical tidal level at the time.

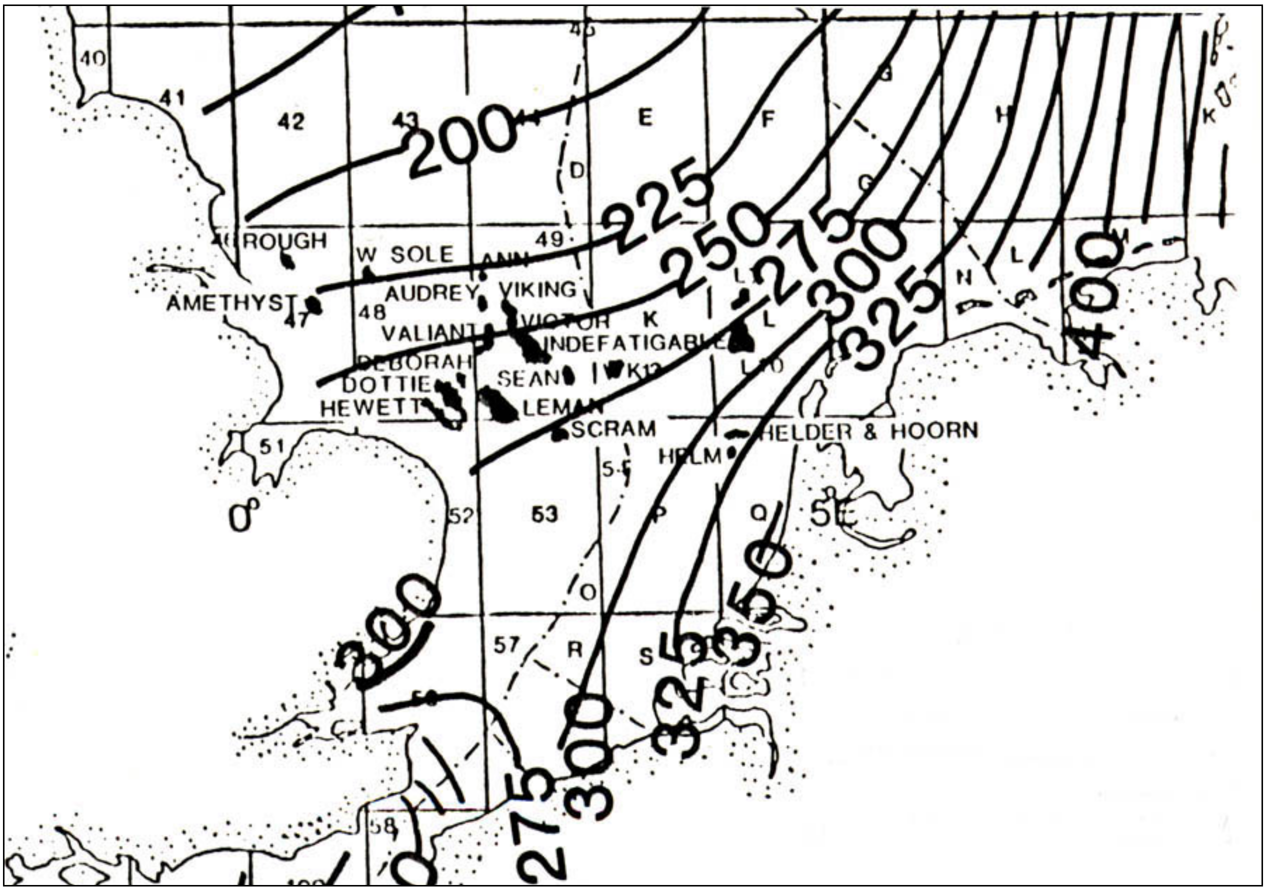

Figure 2.2 Tidal surge levels - expected maximum elevation once in 50 years (cm)

2.3 Total water levels

Extreme water levels (tide + surge) around the UK have been studied by a variety of authors over a number of years (Graff 1981, Flather 1987, and Dixon & Tawn 1994, 1995, 1997). Dixon and Tawn (1997) use the most advanced methods and their work is generally regarded as containing the most accurate information. The results have thus been adopted for use in this study.

Dixon and Tawn (1997) provide estimates of 1-year water levels, together with tabulated values that are added to the 1-year level to obtain higher return period estimates. Results for the A-Class tide gauge sites are detailed, together with each grid point on POL's surge model (spacing 12km) around the coast of the UK. Statistical fitting procedures have been used to obtain spatially smoothed results. The relevant results for Cromer are reproduced in Table 2.1. Dixon and Tawn (1997) recommend that, where the 1-year water level at the location of interest is known with greater confidence (for example, from local gauge measurements) than the estimate provided, then the local estimate should be used. The A-Class tide gauge at Cromer has been analysed to provide this 1-year total water level and the extreme values then estimated following the recommendations made by Dixon and Tawn. Extreme levels at Overstrand, Trimingham, Mundesley, and Bacton are taken 0.09, 0.18, 0.31, and 0.46m lower than at Cromer, respectively, based on differences between MHWS at the three locations. Results of this analysis are given in Table 2.2, giving present-day extreme water levels for Cromer, Overstrand, Trimingham, Mundesley, and Bacton in mODN.

Table 2.1 Water level extrapolation at Cromer (Dixon and Tawn 1997)

Return period (years)	10	25	50	100	250	500
Addition to one year level	0.53	0.74	0.87	1.08	1.28	1.41

Table 2.2 Extreme (present-day) water levels for Cromer, Overstrand, Trimingham, Mundesley, and Bacton (mODN)

Return period (years)		1	10	25	50	100	250	500
Water level (mODN)	**Cromer**	3.17	3.70	3.91	4.04	4.25	4.45	4.58
	Overstrand	3.08	3.61	3.82	3.95	4.16	4.36	4.49
	Trimingham	2.99	3.52	3.73	3.86	4.07	4.27	4.40
	Mundesley	2.86	3.39	3.60	3.73	3.94	4.14	4.27
	Bacton	2.71	3.24	3.45	3.58	3.79	3.99	4.12

2.4 Allowance for climate change

2.4.1 Past climate change estimates

Dixon and Tawn (1997) indicate a rate of sea level rise in the recent past of 1.7mm/yr for this area, approximately equal to the global average value. Wave predictions done in previous HR Wallingford studies off Norfolk and Lincolnshire show significant variability in wave height from year to year, but no significant overall trend. A tentative prediction of future wave conditions for the same area, based on the output of a global meteorological model of present and future wind conditions, does not indicate that a significant change should be expected. Thus, the nationally accepted figure for future sea level rise has been used in this study, and attempts to represent future change in wave conditions are regarded as a sensitivity test rather than a prediction.

2.4.2 Future climate change allowances

The above discussion of tidal levels is based on present-day information and measurements. Because of continuing climate changes, particularly the increase in temperature of the world's oceans, mean sea level is increasing. Predictions from various numerical simulations of the world's atmosphere in the coming few decades, and other sources, seem to be agreed that the present rate of increase in mean sea level will accelerate. Since this will occur over the expected lifetime of a coastal defence structure, it is necessary to anticipate higher tidal levels in any consideration or design of such defences.

Table 4.4 of MAFF (1999) recommends an appropriate precautionary allowance for future mean sea level rise of 6mm/yr for the Anglian region. In the absence of any information to the contrary, it would be normal practice to assume that the future change in the highest water levels will be the same as the change in mean sea level. In this instance, there is some additional information from an ongoing DEFRA-funded study at HR Wallingford into the future vulnerability of sea defences. In calculations for Mablethorpe, HR

Wallingford (2001a) allowed future winds, waves, surges, beach profiles, and tidal ranges to change in addition to mean sea level. This study showed that the 'normal practice' is a fair approximation of the overall change in vulnerability.

To apply the allowance of 6mm/yr, all the predicted present-day water levels are raised by 6mm times the number of years ahead being considered. For example, at the end of a 50-year design life, all levels would be assumed 300mm higher. Note that this has a dramatic effect on the predicted return period of the total water levels presented in Table 2.2 above. At present, the annual chance of the water level rising to over 4.0m ODN at Cromer is only approximately 2%. However, by 2050, this probability will have increased to approximately 10%.

3. TIDAL CURRENTS

Strong tidal currents accompany the rapid spatial changes in tidal range along the coastline of North Norfolk. An initial appraisal of such currents can be gained from the information published on the Admiralty Charts (106, 108) for this coastline. Details on measured current speeds and directions are provided at three locations in and around the study area. These details are reproduced in the following Tables 3.1 to 3.3. Position B is about 14km directly offshore of Mundesley, inshore of the north-western end of Haisborough Sand. Position A is 15km offshore from Sheringham. Using the opposite convention for winds (i.e. direction to which the current is flowing), the directions are given in degrees relative to True North. Thus, just before high water, the current (direction approximately 120-150°N depending on the location) is travelling approximately from the north-west to the south-east.

Table 3.1 Tidal streams – Offshore from Mundesley (from Admiralty Chart 106)

Position B	52° 59.0′ N	001° 35.0′ E	
Time relative to HW at Immingham	Direction	Speed (knots)	
		Spring	Neap
-6hr	327	1.7	1.0
-5hr	327	2.6	1.5
-4hr	327	2.7	1.6
-3hr	327	1.9	1.1
-2hr	327	0.7	0.5
-1hr	147	0.6	0.3
HW	147	1.6	0.9
+1hr	147	2.4	1.4
+2hr	147	2.4	1.5
+3hr	147	1.9	1.2
+4 hr	147	1.1	0.6
+5hr	327	0.1	0.1
+6hr	327	1.6	0.7

Table 3.2 Tidal streams – Offshore from Sheringham (from Admiralty Chart 106)

Position A	53° 05.4′ N	001° 13.2′ E	
Time relative to HW at Immingham	Direction	Speed (knots)	
		Spring	Neap
-6hr	300	1.9	1.0
-5hr	296	2.4	1.2
-4hr	289	2.4	1.2
-3hr	281	1.6	0.8
-2hr	248	0.4	0.2
-1hr	131	0.7	0.4
HW	120	1.6	0.8
+1hr	115	2.1	1.1
+2hr	111	2.1	1.1
+3hr	109	1.6	0.8
+4 hr	087	0.6	0.3
+5hr	326	0.6	0.3
+6hr	301	1.6	0.8

Table 3.3 Tidal streams – Offshore from Horsey (from Admiralty Chart 106)

Position D	52° 50.0′ N	001° 48.0′ E	
Time relative to HW at Immingham	Direction	Speed (knots)	
		Spring	Neap
-6hr	321	1.2	0.7
-5hr	321	2.2	1.3
-4hr	321	2.7	1.5
-3hr	321	2.5	1.4
-2hr	321	1.5	0.8
-1hr	321	0.2	0.1
HW	141	1.2	0.7
+1hr	141	2.4	1.3
+2hr	141	2.5	1.5
+3hr	141	2.1	1.3
+4 hr	141	1.4	0.8
+5hr	141	0.4	0.2
+6hr	312	0.8	0.4

Tables 3.1 to 3.3 provide information on the variation of tidal current velocities throughout both a mean Spring and a mean Neap tide, with speeds given in knots (1 knot ≈ 0.51m/s or 1.16mph). Unfortunately, the time-base for these tables is relative to high water at Immingham. High water at Cromer occurs approximately 30-50 minutes later that at Immingham. Once this adjustment is made, the tables indicate that minimum current speeds (slack water) occur roughly halfway between high and low water. The currents are remarkably rectilinear off Mundesley (probably an effect of the Haisborough Sand) while further north and west there is some variation in current direction with an anticlockwise circulation during the tidal cycle. However, the use of information on tidal currents measured well offshore, and presented using timings relative to Immingham, is not an ideal approach for the study of coastal processes at the coastline of the study area.

For a more detailed appraisal of tidal currents close to this shoreline, therefore, we have used a numerical model. HR has developed a regional tidal flow model of the southern North Sea using the finite element based model TELEMAC (HR Wallingford, 1998). TELEMAC, developed by LNH Paris, uses a completely unstructured grid enabling the detailed simulation of a particular area of interest while using larger model elements to keep any imposed boundary conditions distant.

For the southern North Sea regional model, the model boundaries were from Scarborough to Den Helder in the north with southern boundaries within the English Channel. Imposed tidal levels generated from tidal harmonics drove the model at these boundaries. The finest model resolution has been concentrated around the UK coast with a grid size of 1.5km around the study area.

Since its establishment, the regional model has been widely used, to include strategic studies of sediment transport in the southern North Sea by HR Wallingford (2001b). In this study, HR Wallingford included comparisons of various versions of the model with tidal currents synthesised from harmonics in the area. This model can provide predictions of the rise and fall of the tide, and the simultaneous tidal currents, at any location. Figure 3.1 shows a portion of seabed as represented in this model. On this figure, the coastline extends from approximately Blakeney Point to the west to Cart Gap, Eccles to the east. The seabed contours are shown relative to ODN and extend offshore to beyond the 20m contour.

The inset figures show the tidal rise and fall (solid line) and the tidal current speed at Points A, O and M about 5km offshore from Cromer, Overstrand and Mundesley respectively, on about the 20mOD contour. It is clear from this that the times of greatest current speed coincide reasonably closely with the times of high and low water. To be more precise, maximum flood currents (i.e. going to the east) occur about one hour later than high water, and maximum ebb flows about one hour after low water.

Figures 3.2 to 3.5 are snapshots of tidal currents during the simulation of a series of spring tides beginning 21 March 2000, in the form of arrows whose length indicates the current speed and orientation indicates the current direction. The tidal currents can be seen to be generally coastline parallel with some directional changes caused by the offshore sandbanks, which are a feature of the area. Offshore, near the locations of the Admiralty measurements from Charts 106 and 108, the model results agree well, in both speed and direction, with the results presented in the tables above. Current speeds are slightly lower closer inshore because of the increased frictional resistance of the seabed. However, they are predicted to be about 0.8m/s (1.5kt) at high water, slightly slower at about 0.6m/s (1.2kt) at low tide. (Note that, at low tide, water depths close to the shore are less than at high tide, and this further increases the frictional resistance). These current speeds, on their own, are capable of mobilising and transporting large quantities of seabed sediments up to the size of small gravel. The added effects of breaking waves, which disturb and agitate much larger gravel and shingle particles, means that tidal currents along this coast strongly affect beach sediment transport.

A particular feature of this part of the Norfolk coastline is that the strongest tidal currents will occur at about the time of high water during an exceptionally large tide. While this occurs regularly during Spring tides, it will also occur during storm surges, which will increase the total water level and add to the eastward flowing currents. On such occasions, winds are normally from the north or north-west, and will therefore create large waves along the Cromer frontage as well as affecting the tides.

Such a combination of events will occur several times during a winter, and will have a strong effect on beaches, producing sediment transport both along the shore and offshore, with a flattening of the beach profile. Such events are referred to by local fishermen as ‘scouring tides’, and this is an appropriate if unusual terminology. Such strong currents close to the shoreline will interact strongly with groynes or breakwaters, and this issue needs to be borne in mind when considering the design of such structures.

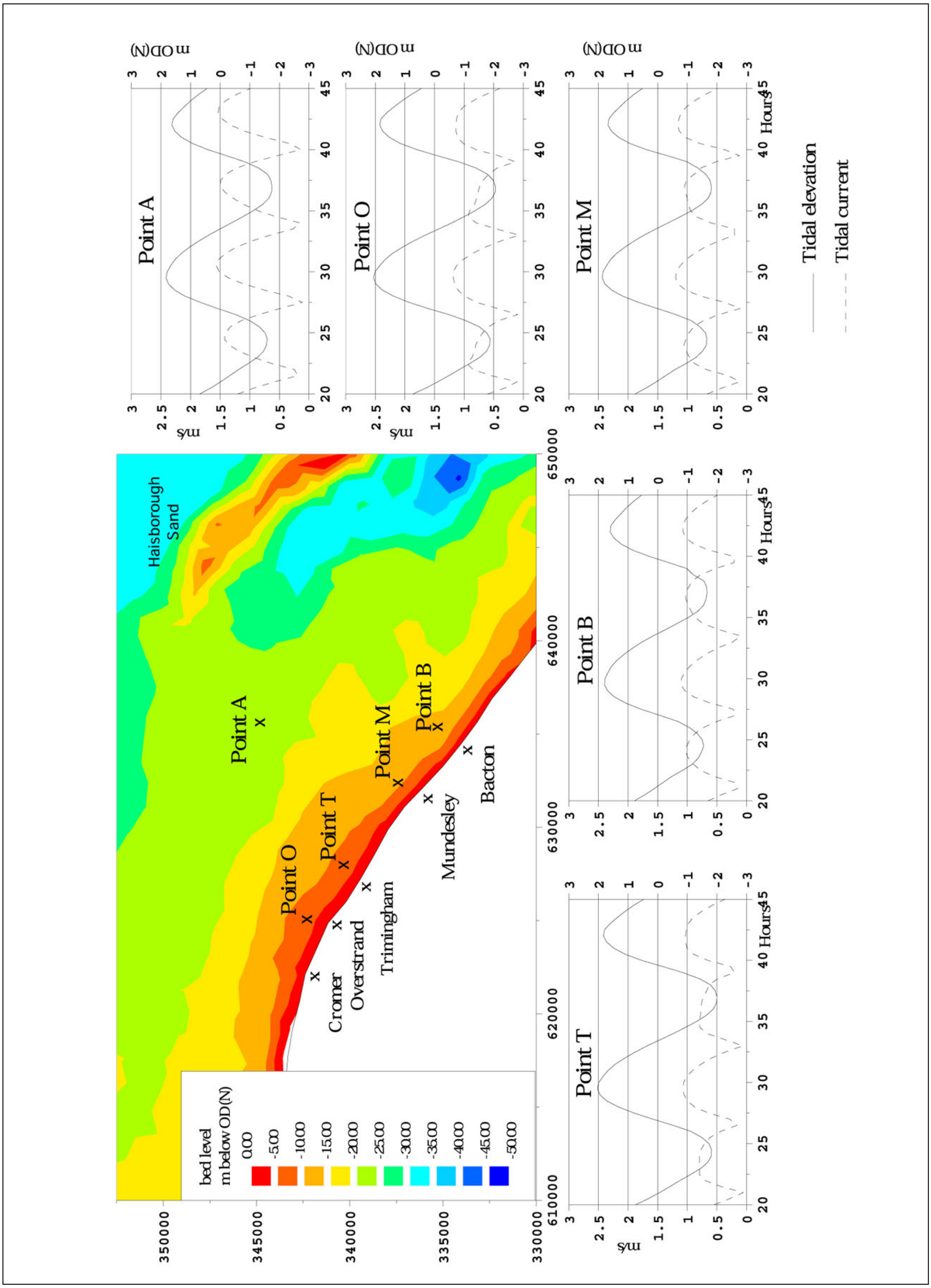

Figure 3.1 Seabed bathymetry between Mundesley and Winterton Ness

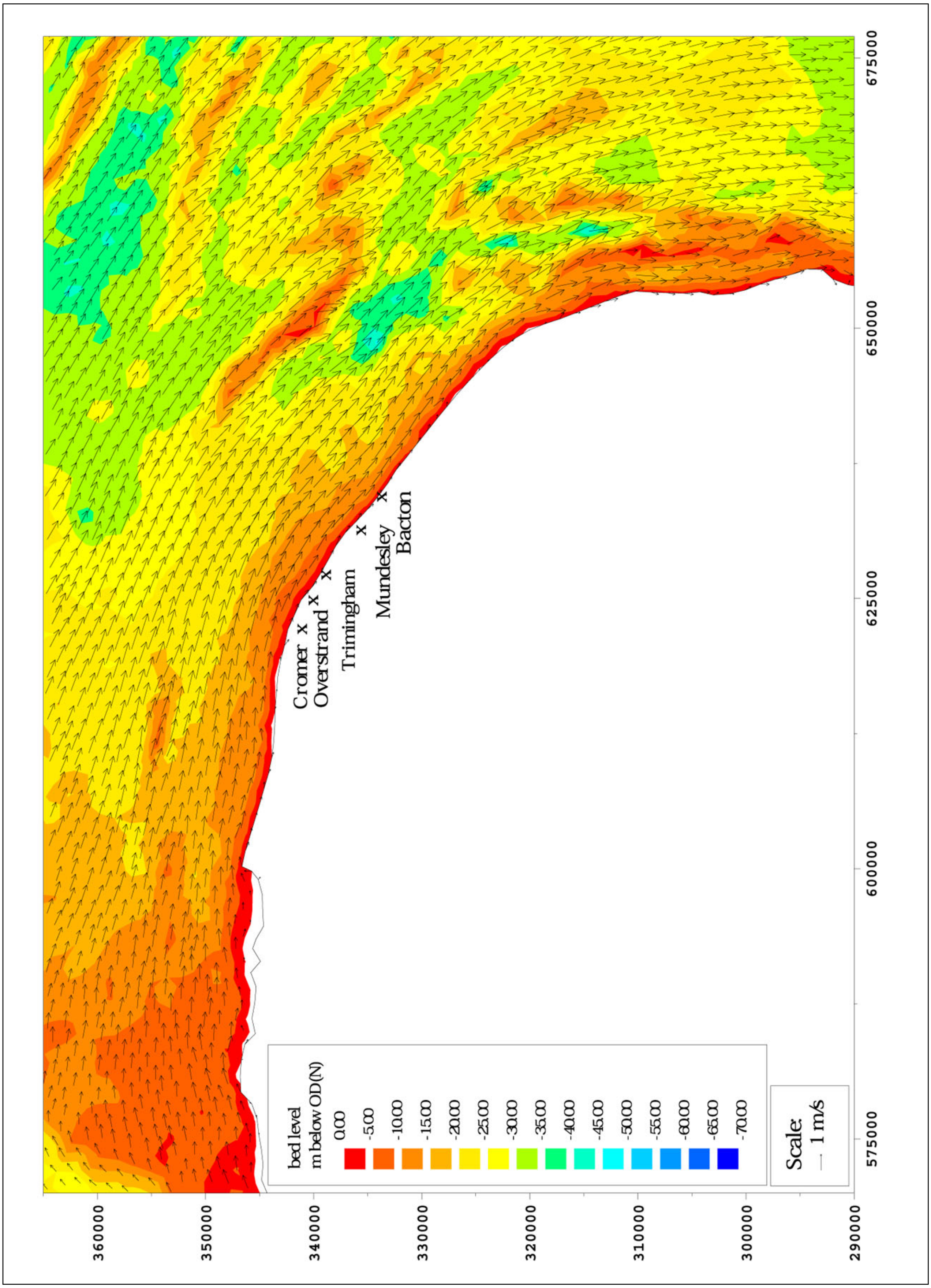

Figure 3.2 Ebb tidal currents on a spring tide

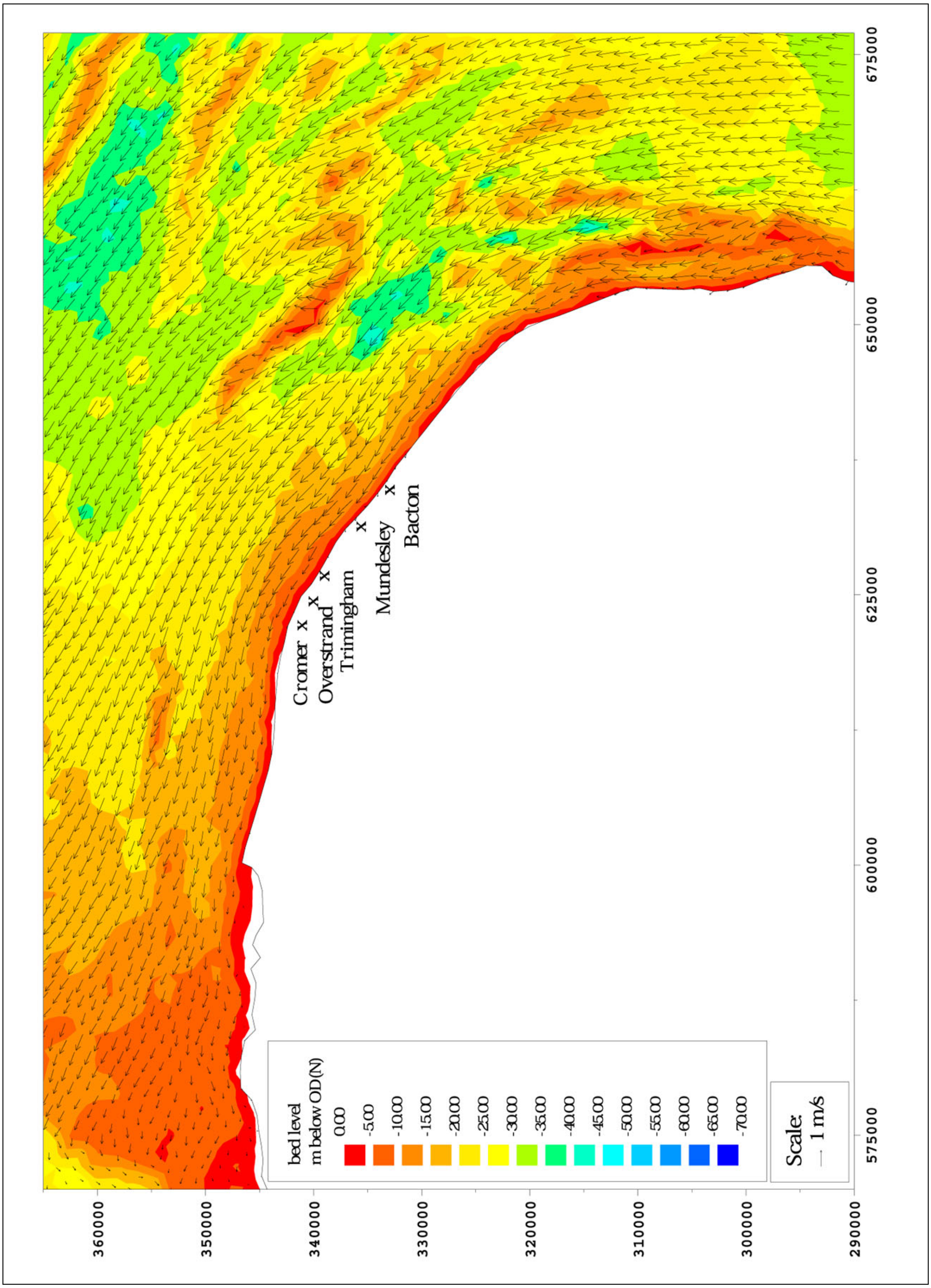

Figure 3.3 Flow tidal currents on a spring tide

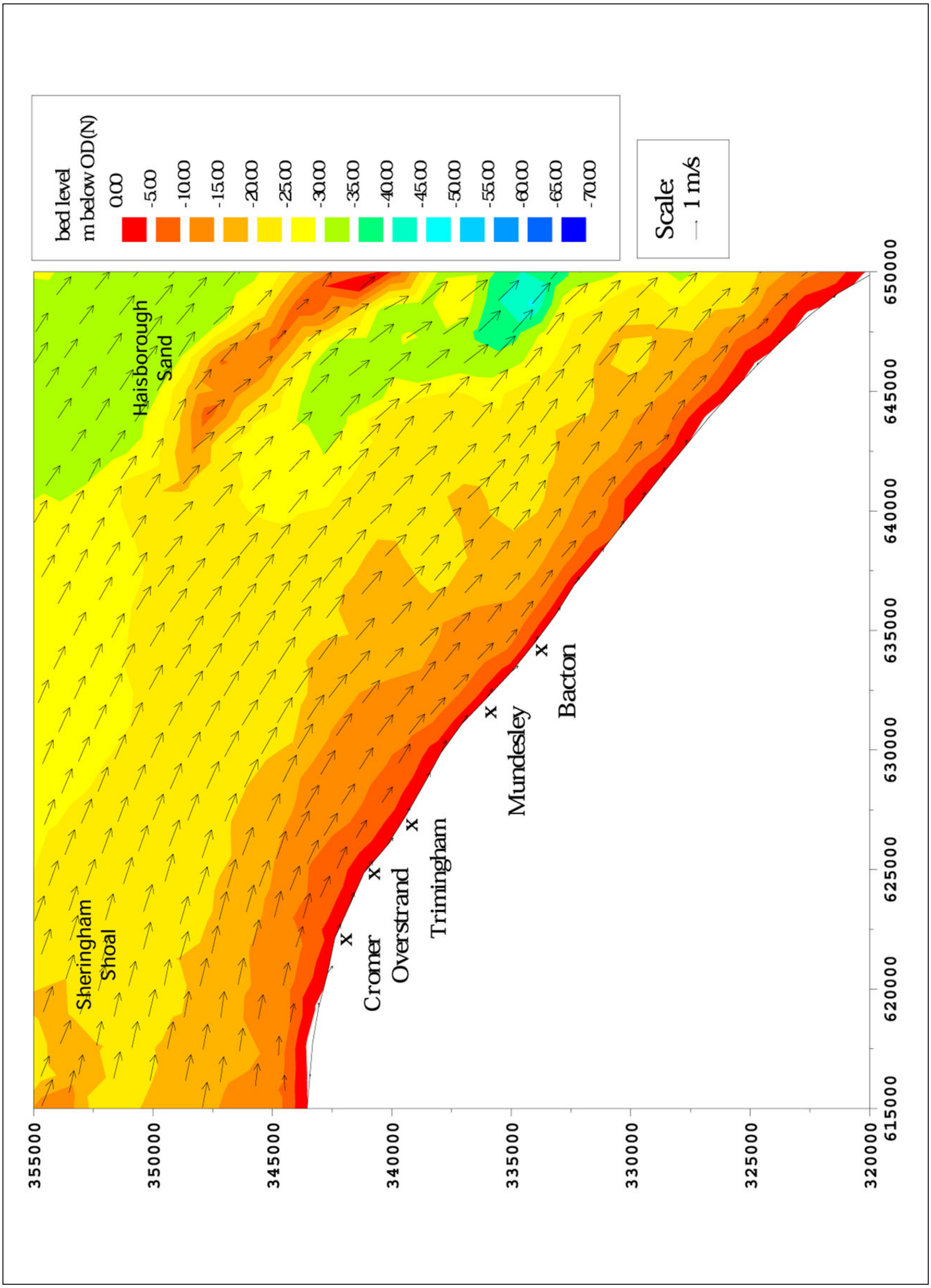

Figure 3.4 Ebb tidal currents on a spring tide (local area)

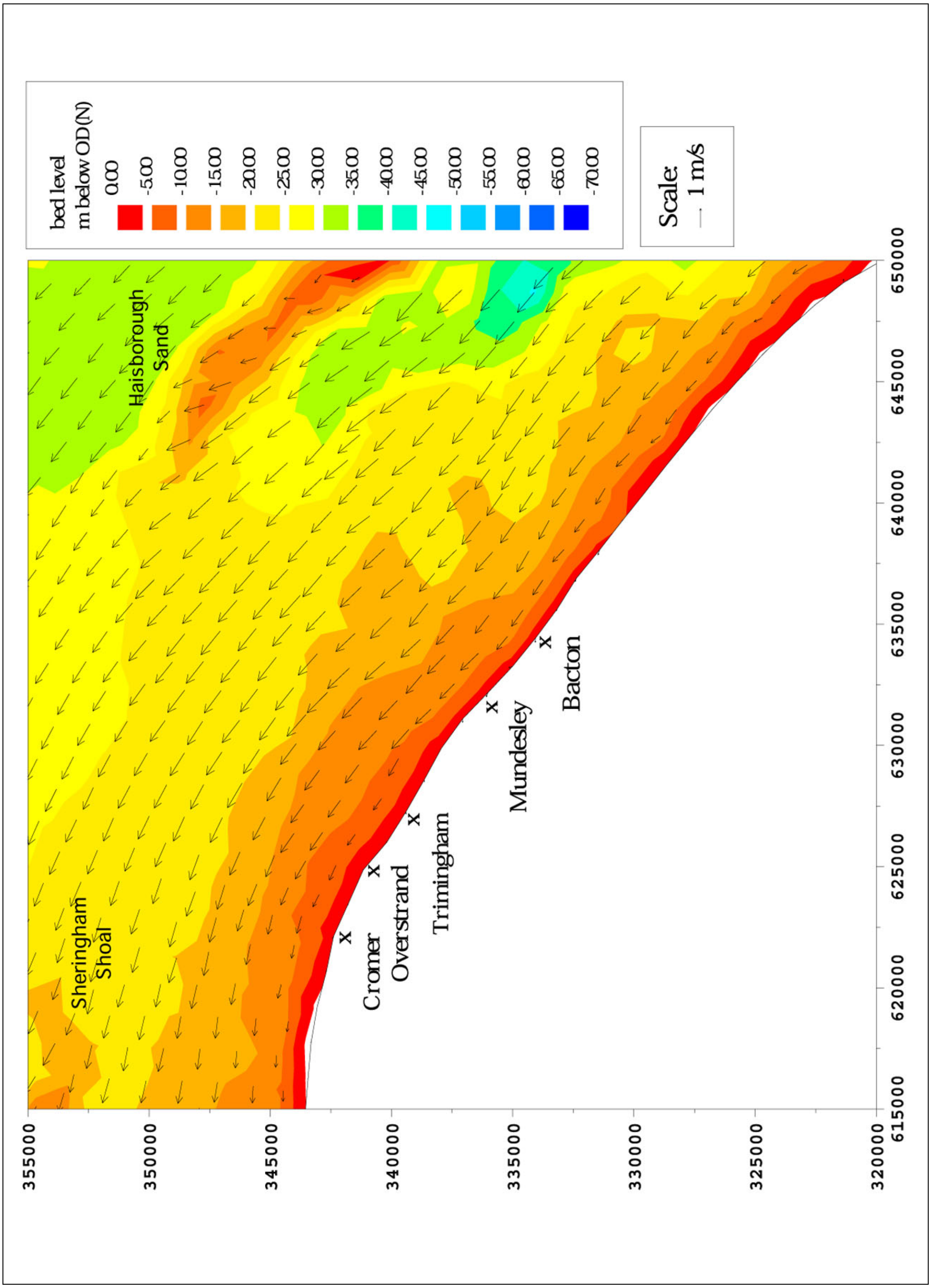

Figure 3.5 Flow tidal currents on a spring tide (local area)

4. WAVE CONDITIONS

4.1 Introduction

The major force for changes in the coastline of North Norfolk and of its beaches is wave action. Along the study area, the coastline is exposed to waves generated within the North Sea from all directions between approximately 300°N and 90°N. However, waves are predominately from between North (0°N) and 70°N, since the fetch lengths for this sector all exceed 500km (see Figure 4.2). For this study, it is necessary to obtain information on wave conditions close to the coastline in order to predict longshore sediment transport rates, and the future evolution of the shoreline. Such predictions will also provide estimates of the largest waves likely to occur, and these will be useful in the design of any coastal structures in the development of a defence scheme, following the completion of this strategy study. Wave conditions were predicted both offshore and at ten nearshore points on the -3.25mOD contour (see Figure 4.1). Full results for Overstrand, Trimingham, Mundesley, and Bacton are provided in this report.

4.2 Predicting offshore wave conditions

As an initial step in predicting 'nearshore' wave conditions, it is necessary to predict 'offshore' wave conditions, i.e. in deep water ignoring the effects of the changing water depth closer to the coast. For this study, offshore wave conditions were predicted using a numerical model named HINDWAVE. This model simulates the growth of waves under the action of winds and requires, as input data, information on the area over which wave are created and on wind conditions measured close to the study frontage. This modelling approach has been used several times previously for studies of the coastline of East Anglia, for example for the detailed study of the coastal defences at Sheringham, in 1994 (HR Wallingford 1994).

The model has been verified by comparison with long-term visually observed wave climate data off the North Norfolk coast, at Smith's Knoll light vessel, as part of the Anglian Coastal Management Study carried out for the NRA in 1988. HR Wallingford (1988) provides a comparison between the HINDWAVE and Smith's Knoll wave climates for this study. In this instance, the model input was taken from was sequential land-based wind data from Gorleston (near Great Yarmouth). However, the wind speeds were appropriately increased to represent over-water conditions and extended in duration using synthetic wind data from an UK Met Office weather model.

The wave modelling for the present study used the same HINDWAVE model, but with a somewhat improved user interface. Again, sequential wind data from Gorleston was used, with the same adjustments to the wind speeds as used in the original 1988 study. However, the wind data available from this site now covers a longer period, i.e. from 1978 to 1994, extended to 2001 using weather model data allowing us to produce corresponding offshore wave conditions for a period of 23 years.

4.3 Allowance for the effects of Haisborough Sand

A second validation of the results of the HINDWAVE model, using wave measurements made well offshore from Cromer, was also undertaken during the 1988 study. In view of the results obtained, this validation exercise was re-visited during a subsequent research study in 1989. This second study showed the benefits of making some allowance for wave attenuation over the offshore banks. Predictions with no allowance for banks tended to be too high, whilst the refined predictions were significantly better. HR Wallingford (1989) gives a comparison between the wave measurements off Cromer (the 'standard' HINDWAVE predictions and the modified, 'shallow water' HINDWAVE results.

This earlier work therefore indicated that the standard HINDWAVE model would be likely to over-estimate wave conditions unless the effects of Haisborough Sand were taken into account. The first step in the wave prediction process in the recent study was therefore to adjust the standard HINDWAVE prediction for a location offshore of Cromer to account for the dissipation of wave energy over this sandbank. This is particularly important for waves approaching from the eastern sector.

At low tide, especially, the water depths over this bank will cause significant wave breaking, and hence a reduction in wave heights from the seawards to the landwards side of the bank. This effect will vary in intensity along the length of the bank, depending on its crest height.

For the present study, however, the main emphasis is on the prediction of waves at times of high tidal level, when the beaches and cliffs will be most strongly affected by wave action. This is also the situation when coastal defence structures will be most as risk from damage by waves. We are also only interested in calculating a 'representative' wave climate in this strategic study, rather than very detailed, location-specific conditions for the design of a structure. Such more complicated and costly calculations would be needed at the 'scheme appraisal' stage for any proposed coastal defence, as part of the detailed design calculations needed at that time.

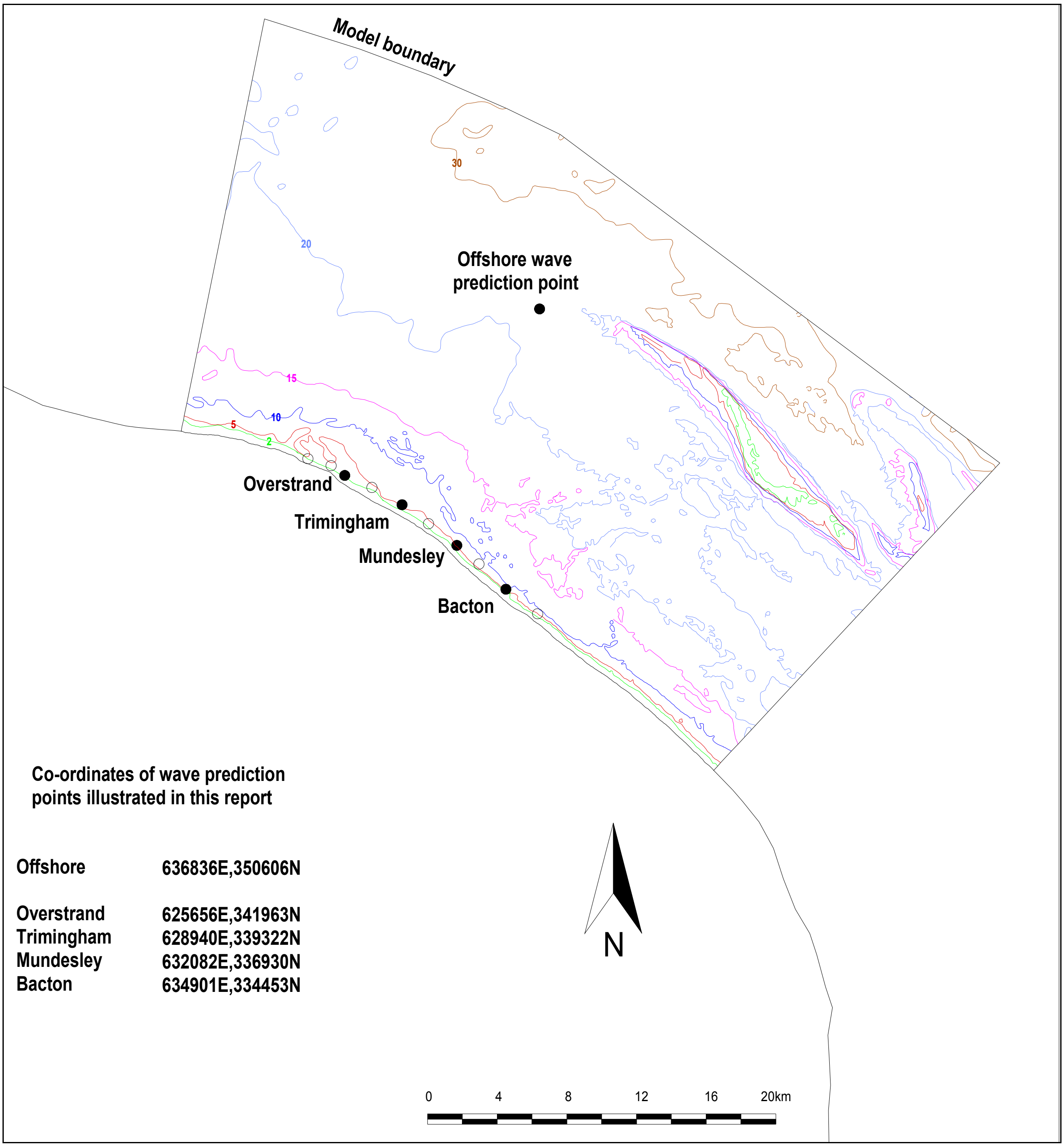

Figure 4.1 Offshore and nearshore wave prediction points

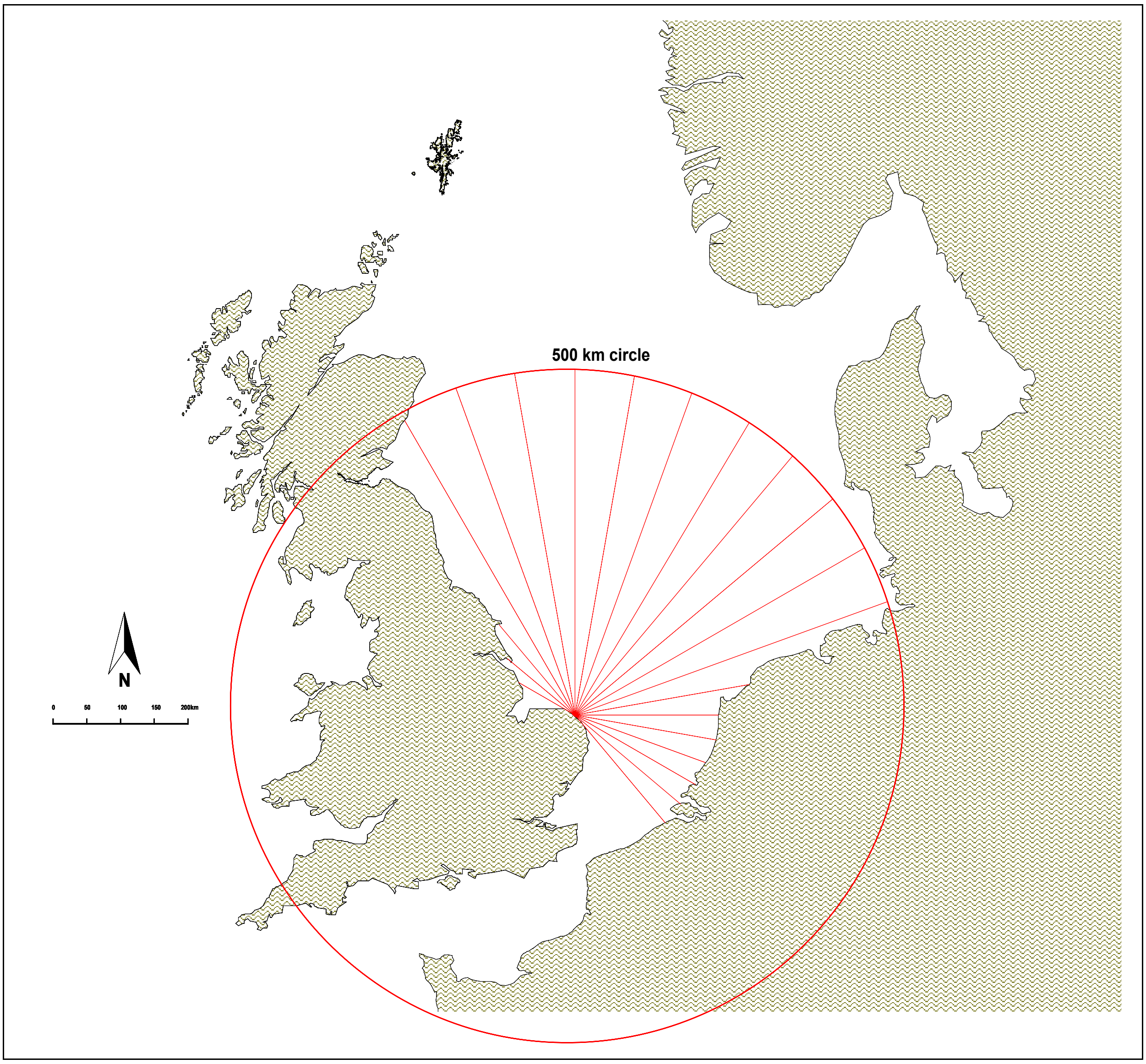

Figure 4.2 Fetch lengths for the generation of waves at Cromer

Because of this, a simplified approach was taken to account for the effects of Haisborough Sand on the offshore wave conditions. This simplification involved calculating the depth-limited maximum wave height over its crest and hence limiting the maximum wave heights that can occur on its landwards side. The results from the two-stage prediction of offshore waves, described above, are in the format of wave conditions, i.e. height, period, and direction, for each hour of the 23 years for wind data. While this amount of information is too substantial to present in this report, it is retained in electronic format for potential use in the future. For the purposes of this report, only a summary of the wave information is presented. One straightforward and visually appealing method of summarising the data is to use a wave rose as shown in Figure 4.3. This gives information on the frequency of occurrence and height of waves approaching the shore location from different directions.

It can be seen that the largest waves of all are likely to arrive from about 030°N, but the most frequent wave directions are from the north-west (330°N). Alternative methods of summarising this offshore wave data are provided in Tables 4.1 and 4.2, which provide information on the probability of wave heights against direction, and wave height against wave period, respectively.

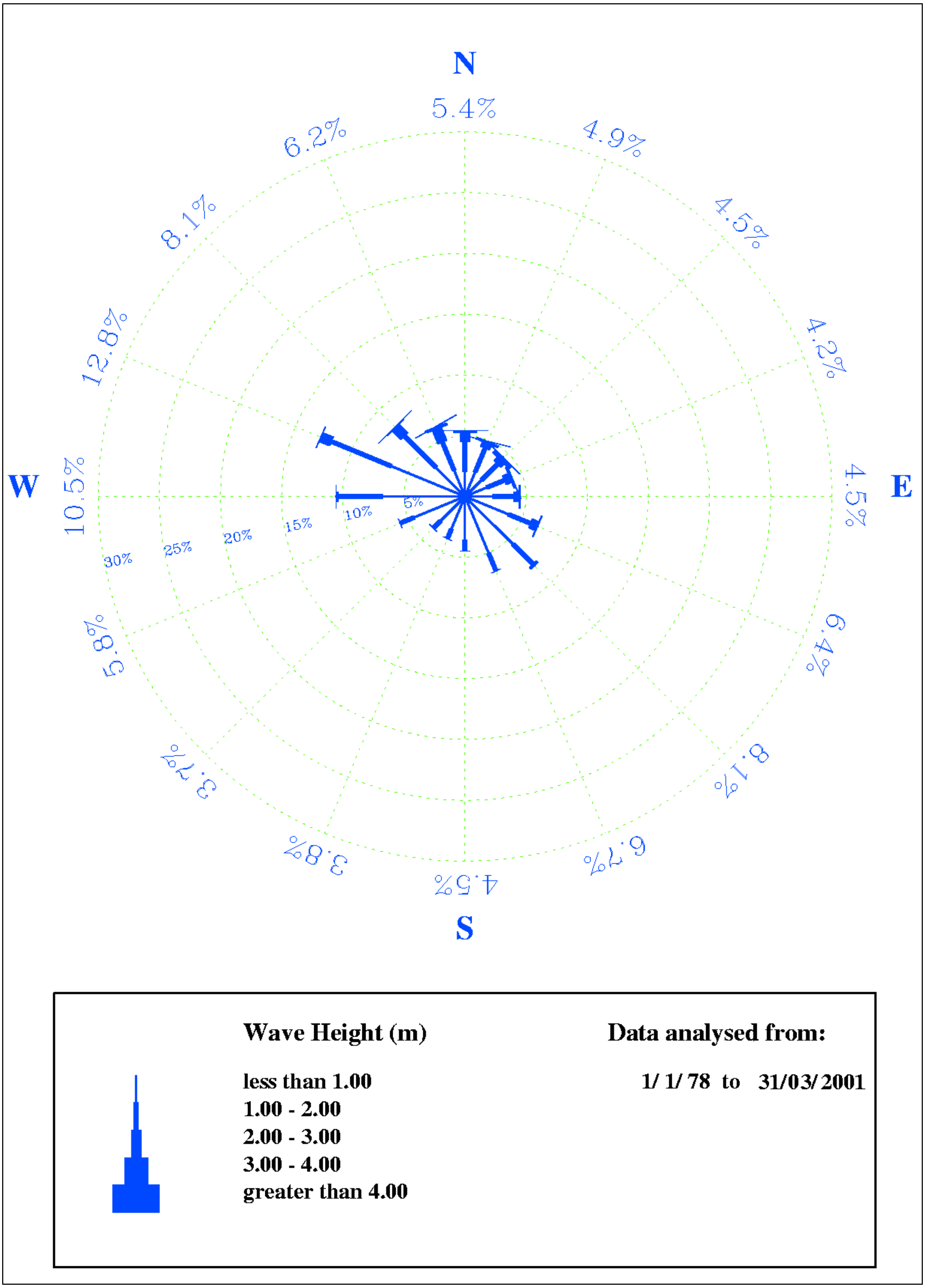

Figure 4.3 Wave rose showing offshore wave conditions

Table 4.1 Annual offshore wave climate – Wave height against mean wave period occurrence table *

H_s (m)	Mean wave period T_m (seconds)									
	0–1	1-2	2-3	3-4	4-5	5–6	6-7	7-8	8-9	9-10
0–1	0	314	27860	24945	0	0	0	0	0	0
1-2	0	0	1	13477	15751	2834	0	0	0	0
2-3	0	0	0	8	1578	4520	0	0	0	0
3-4	0	0	0	0	16	510	682	0	0	0
4-5	0	0	0	0	0	26	131	0	0	0
5-6	0	0	0	0	0	4	1	0	0	0
All H_s	0	314	27861	38430	17345	7894	814	0	0	0

Table 4.2 Annual offshore wave climate –Wave height against wave direction occurrence table *

H_s (m)	Mean wave direction (degrees North)											
	345-015	015-045	045-075	075-105	105-135	135-165	165-195	195-225	225-255	255-285	285-315	315-345
0–1	2570	2545	2470	2927	5142	6475	4527	3502	4669	8162	6971	3158
1-2	2886	2511	2120	2114	2399	2514	1325	1188	1401	4182	5769	3551
2-3	952	529	641	593	578	92	15	18	23	188	1011	1464
3-4	199	258	301	149	42	0	0	0	0	7	65	187
4-5	20	42	62	8	1	0	0	0	0	0	5	19
5-6	5	0	0	0	0	0	0	0	0	0	0	0
All H_s	6732	5885	5594	5791	8161	9081	5867	4708	6093	12539	13821	8379

* Based on HINDWAVE predictions for 1 January 1978 to 31 March 2001, with data expressed in parts per hundred thousand; total number of wave predictions is 203784.

4.4 Nearshore wave conditions

Having predicted wave conditions in relatively deep water offshore, it was then necessary to calculate how these wave conditions alter as they travel towards the shoreline. As the water depths become shallower, so the direction and height of the waves alters as a result of refraction and shoaling. Because of the irregular nature of the seabed contours, it was necessary in this study to carry out a further numerical modelling exercise to predict nearshore wave conditions.

This modelling exercise involved creating a digital representation of the seabed offshore from Cromer to Bacton, using a combination of information from Admiralty charts, and the recent (2000) survey of the nearshore seabed. This latter survey was commissioned by North Norfolk DC as an early part of the strategic study of the defences at Cromer. The resulting bathymetric grid is depicted in Figure 4.4.

The offshore wave conditions were assumed to occur (uniformly) along the seaward boundary of this grid, and the grid itself formed the domain for a computational method for predicting wave transformation between the boundary and selected locations closer inshore. The method used for these predictions was the TELURAY model, which uses the concept of following wave ‘rays’ between the inshore locations and the seaward edge of the grid. Wave rays are lines perpendicular to the wave crests that run in the direction of wave propagation.

In brief, however, a matrix specifying the wave energy as a function of wave period and direction represents each hourly offshore wave condition. Using this matrix (and three matrices of identical size that summarise how wave rays travel between the inshore location and the edge of the bathymetric grid), the main parameters of the corresponding inshore wave conditions are predicted. The principal output is then the nearshore wave height, period and direction. Wave direction is particularly important, as this parameter is central for calculating the movement of beach sediment along the coast.

The wave transformation method used allows the (long) hourly sequence of offshore wave conditions to be converted into a corresponding sequence of nearshore wave conditions. Again, it is only necessary, in this report, to provide a summary of this substantial volume of results for four representative locations of interest, namely Overstrand, Trimingham, Mundesley and Bacton. Figures 4.5-4.8 show wave roses, which can be compared directly with the Figure 4.3 for the offshore wave conditions. Notice that there is less directional spread in the nearshore wave roses, because of the effects of wave refraction. Waves from 90°N have been substantially reduced in both height and frequency of occurrence compared to conditions offshore. Waves from the north-west sector (300-330°N) are predicted to occur much more frequently than for other directions, but the largest waves of all arrive from the North (030°N). Tables 4.3-4.10 present information on the nearshore wave conditions as probability tables in the same format used for the offshore waves (Tables 4.1 and 4.2).

The results of extremes analyses, based on fitting Weibull distributions to the overall wave height distributions given in Tables 4.4, 4.6, 4.8 and 4.10, are given in Table 4.11. The corresponding wave periods, derived from the steepness ($2\pi H_s/gT_m^2$) of the highest few percent of waves in Tables 4.3, 4.5, 4.7 and 4.9, are also listed in Table 4.11.

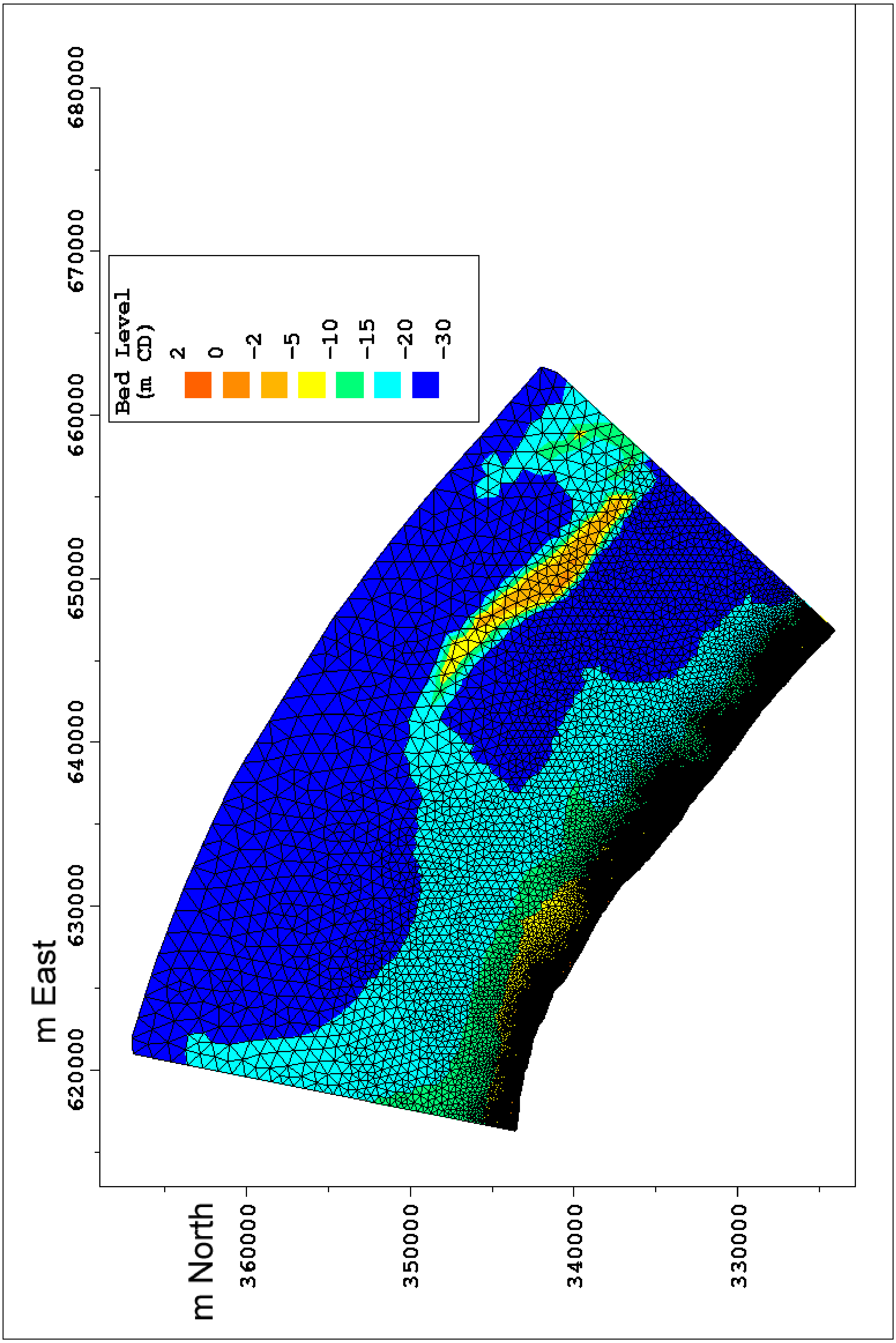

Figure 4.4 **Bathymetric grid used for wave transformation modelling**

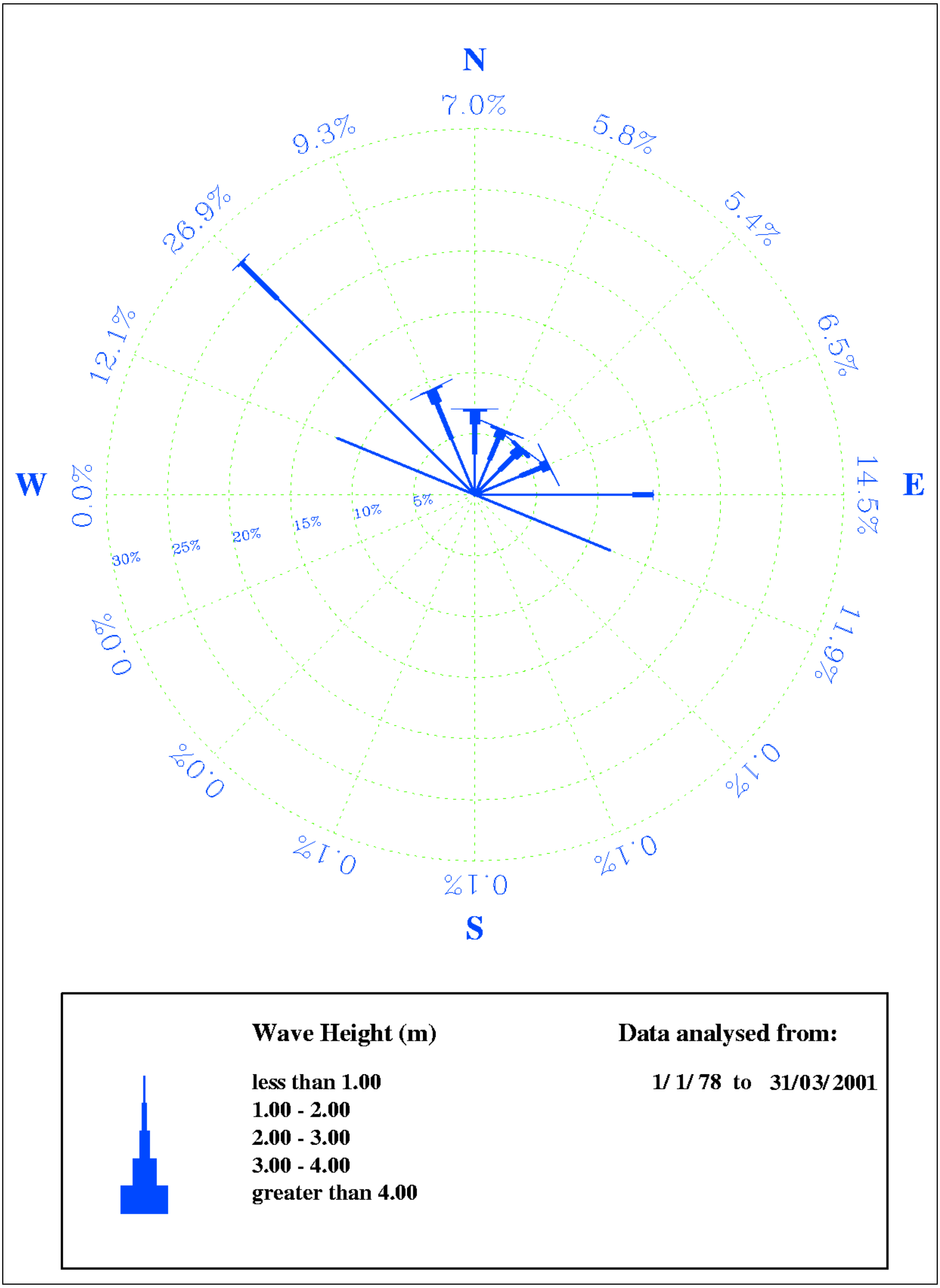

Figure 4.5 **Wave rose showing inshore wave conditions – Overstrand**

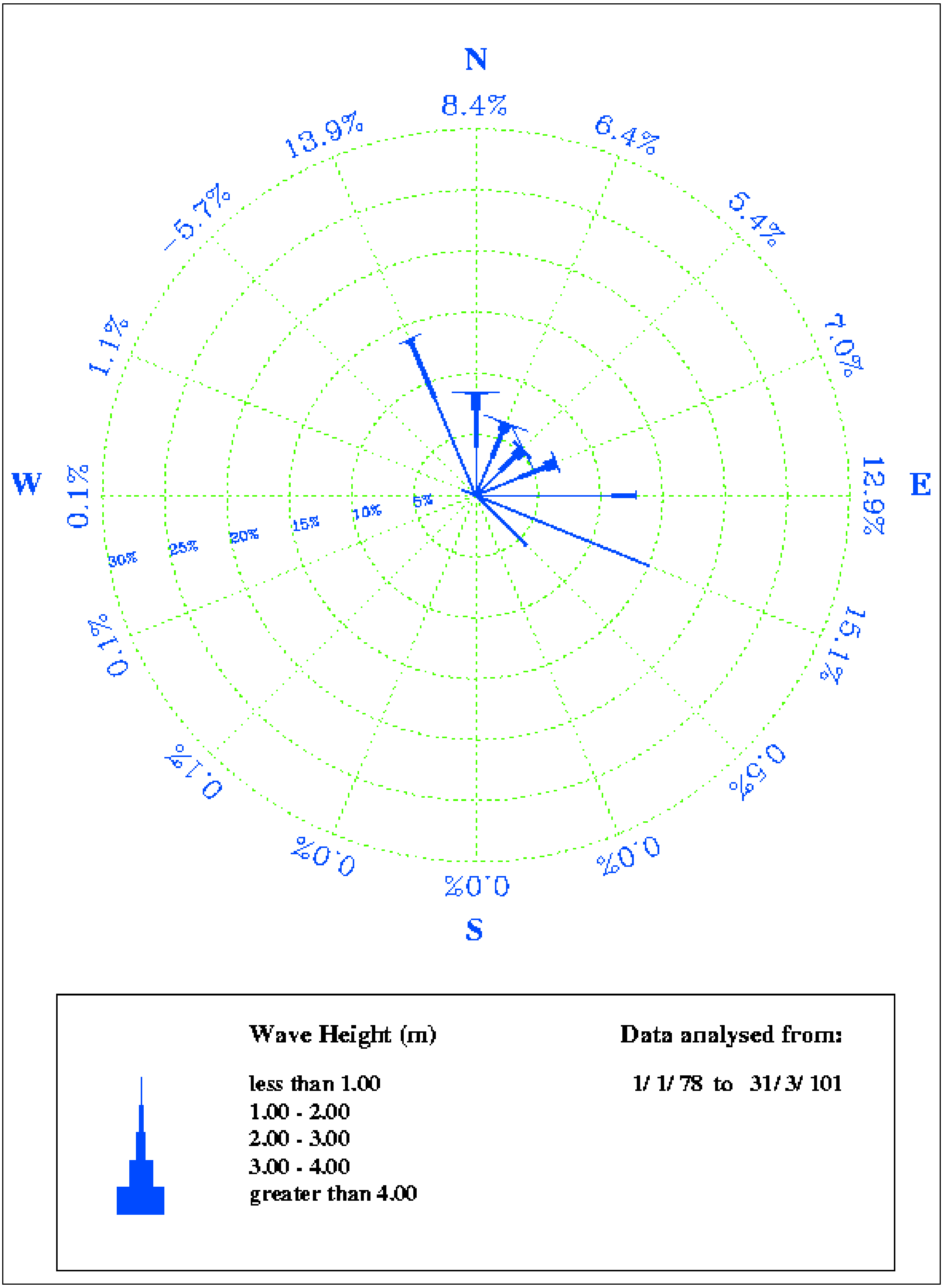

Figure 4.6 Wave rose showing inshore wave conditions – Trimingham

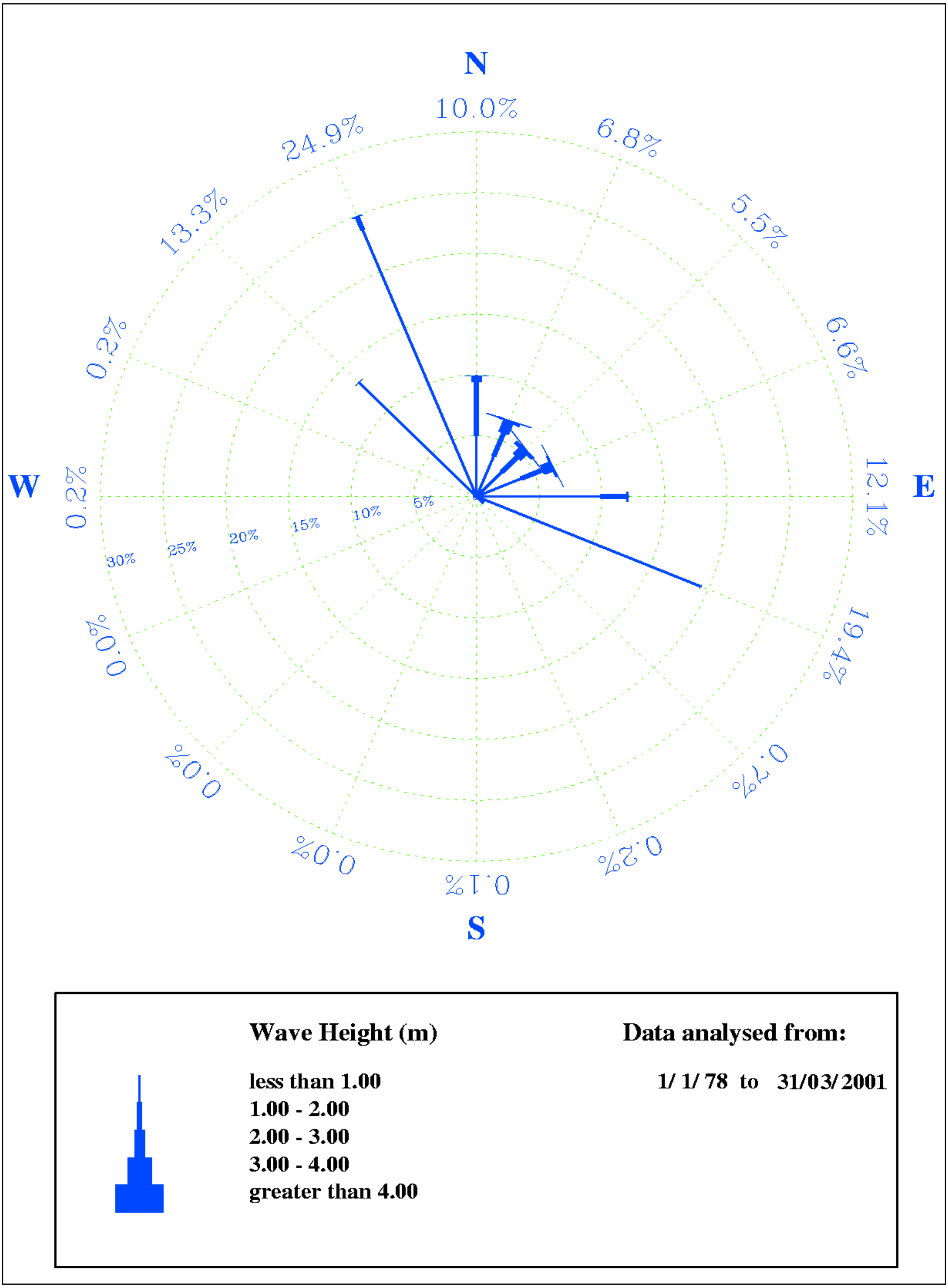

Figure 4.7 **Wave rose showing inshore wave conditions – Mundesley**

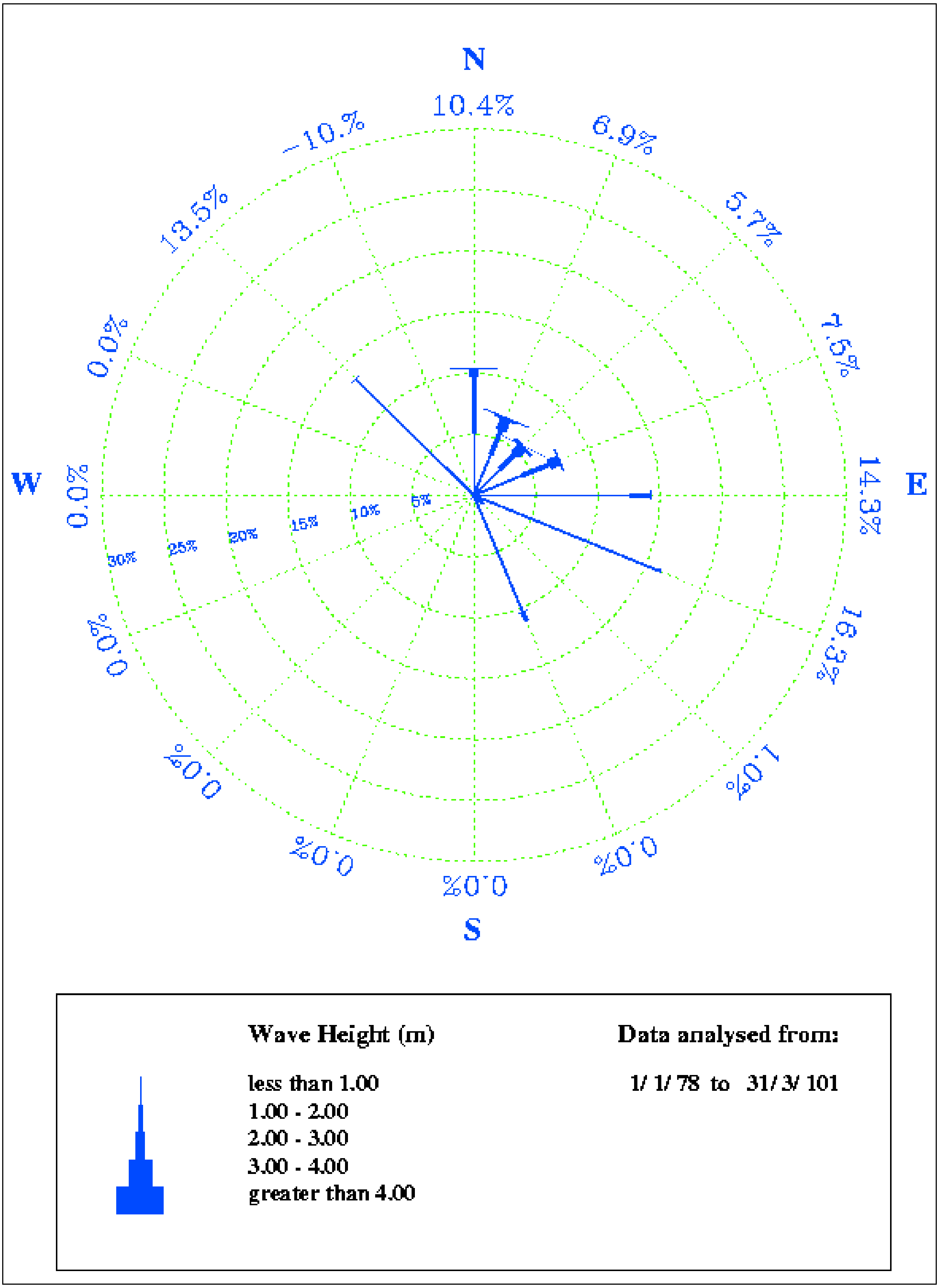

Figure 4.8 Wave rose showing inshore wave conditions – Bacton

Table 4.3 Annual inshore wave climate – Overstrand – Wave height against mean wave period occurrence table *

H_s (m)	Mean wave period T_m (seconds)									
	0–1	**1-2**	**2-3**	**3-4**	**4-5**	**5–6**	**6-7**	**7-8**	**8-9**	**9-10**
0–1	0	620	22497	33075	12619	1739	26	0	0	0
1-2	0	0	0	350	11853	4806	4	0	0	0
2-3	0	0	0	0	171	3915	170	0	0	0
3-4	0	0	0	0	0	140	584	0	0	0
4-5	0	0	0	0	0	1	71	0	0	0
5-6	0	0	0	0	0	4	11	0	0	0
All H_s	0	620	22497	33425	24643	10605	866	0	0	0

Table 4.4 Annual inshore wave climate – Overstrand – Wave height against wave direction occurrence table *

H_s (m)	Mean wave direction (degrees North)											
	345-015	**015-045**	**045-075**	**075-105**	**105-135**	**135-165**	**165-195**	**195-225**	**225-255**	**255-285**	**285-315**	**315-345**
0–1	3881	3467	3833	11927	11120	293	311	167	141	570	27647	7218
1-2	3022	2093	2118	2583	0	0	0	0	0	0	2115	5082
2-3	1325	728	966	242	0	0	0	0	0	0	7	988
3-4	207	168	278	8	1	1	0	0	0	0	0	61
4-5	20	36	9	0	0	0	0	0	0	0	0	7
5-6	14	1	0	0	0	0	0	0	0	0	0	0
All H_s	8469	6493	7204	14760	11121	294	311	167	141	570	29769	13356

* Based on HINDWAVE predictions for 1 January 1978 to 31 March 2001, with data expressed in parts per hundred thousand; total number of wave predictions is 203784.

Table 4.5 Annual inshore wave climate – Trimingham – Wave height against mean wave period occurrence table *

H_s (m)	Mean wave period T_m (seconds)									
	0–1	**1-2**	**2-3**	**3-4**	**4-5**	**5–6**	**6-7**	**7-8**	**8-9**	**9-10**
0–1	0	754	24268	34026	12207	2296	404	0	0	0
1-2	0	0	0	1296	8659	4578	42	0	0	0
2-3	0	0	0	0	23	3245	221	0	0	0
3-4	0	0	0	0	0	73	501	0	0	0
4-5	0	0	0	0	0	4	53	0	0	0
5-6	0	0	0	0	0	0	1	0	0	0
All H_s	0	734	24268	35322	20889	10196	1222	0	0	0

Table 4.6 Annual inshore wave climate – Trimingham – Wave height against wave direction occurrence table *

H_s (m)	Mean wave direction (degrees North)											
	345-015	**015-045**	**045-075**	**075-105**	**105-135**	**135-165**	**165-195**	**195-225**	**225-255**	**255-285**	**285-315**	**315-345**
0–1	5051	3779	4317	13641	11820	32	40	75	91	78	10675	24361
1-2	3572	2515	2294	2032	2	1	0	0	0	0	0	4161
2-3	1367	770	1038	191	0	0	0	0	0	0	0	121
3-4	156	191	214	6	0	0	0	0	0	0	0	7
4-5	15	43	0	0	0	0	0	0	0	0	0	0
5-6	0	1	0	0	0	0	0	0	0	0	0	0
All H_s	10161	7299	7863	15870	11822	33	40	75	91	78	10675	28650

* Based on HINDWAVE predictions for 1 January 1978 to 31 March 2001, with data expressed in parts per hundred thousand; total number of wave predictions is 203784.

Table 4.7 Annual inshore wave climate – Mundesley – Wave height against mean wave period occurrence table *

	Mean wave period T_m (seconds)									
H_s (m)	0–1	1-2	2-3	3-4	4-5	5–6	6-7	7-8	8-9	9-10
0–1	0	808	24110	36762	13200	1532	28	0	0	0
1-2	0	0	1	1101	7711	3873	0	0	0	0
2-3	0	0	0	0	41	2665	231	0	0	0
3-4	0	0	0	0	0	60	476	0	0	0
4-5	0	0	0	0	0	4	52	0	0	0
5-6	0	0	0	0	0	0	0	0	0	0
All H_s	0	808	24110	37863	20952	8134	787	0	0	0

Table 4.8 Annual inshore wave climate – Mundesley – Wave height against wave direction occurrence table *

	Mean wave direction (degrees North)											
H_s (m)	345-015	015-045	045-075	075-105	105-135	135-165	165-195	195-225	225-255	255-285	285-315	315-345
0–1	6237	3990	4046	11115	16262	58	94	80	31	41	3504	30981
1-2	5244	2309	2189	2511	10	6	6	0	0	0	0	411
2-3	779	765	1052	278	0	2	0	0	0	3	11	47
3-4	42	163	315	16	0	0	0	0	0	0	0	42
4-5	11	30	15	0	0	0	0	0	0	0	0	1
5-6	0	0	0	0	0	0	0	0	0	0	0	0
All H_s	12313	7257	7617	13920	16272	66	100	80	31	44	3515	31482

* Based on HINDWAVE predictions for 1 January 1978 to 31 March 2001, with data expressed in parts per hundred thousand; total number of wave predictions is 203784.

Table 4.9 Annual inshore wave climate – Bacton – Wave height against mean wave period occurrence table *

H_s (m)	Mean wave period T_m (seconds)									
	0–1	1-2	2-3	3-4	4-5	5–6	6-7	7-8	8-9	9-10
0–1	0	852	25293	37405	9869	2544	801	22	0	0
1-2	0	0	0	1166	6596	4507	2	0	0	0
2-3	0	0	0	0	43	2705	139	0	0	0
3-4	0	0	0	0	0	55	427	0	0	0
4-5	0	0	0	0	0	4	40	0	0	0
5-6	0	0	0	0	0	0	0	0	0	0
All H_s	0	852	25293	38571	19508	9815	1409	22	0	0

Table 4.10 Annual inshore wave climate – Bacton – Wave height against wave direction occurrence table *

H_s (m)	Mean wave direction (degrees North)											
	345-015	015-045	045-075	075-105	105-135	135-165	165-195	195-225	225-255	255-285	285-315	315-345
0–1	7137	4099	4551	14884	13586	15	5	11	2	14	1627	30854
1-2	5283	2445	2548	1900	10	6	6	0	0	0	0	75
2-3	869	839	1054	63	0	2	0	0	0	3	12	46
3-4	56	214	212	0	0	0	0	0	0	0	0	0
4-5	11	33	0	0	0	0	0	0	0	0	0	0
5-6	0	0	0	0	0	0	0	0	0	0	0	0
All H_s	13356	7630	8365	16847	13596	23	11	11	2	17	1639	30975

* Based on HINDWAVE predictions for 1 January 1978 to 31 March 2001, with data expressed in parts per hundred thousand; total number of wave predictions is 203784.

Table 4.11 Extreme wave conditions for Overstrand, Trimingham, Mundesley, and Bacton

Return period (years)	Significant wave height (m) and mean wave period (s)							
	Overstrand		Trimingham		Mundesley		Bacton	
	H_s	T_m	H_s	T_m	H_s	T_m	H_s	T_m
0.1	3.4	6.3	3.2	6.1	3.1	6.0	3.1	6.0
1	4.6	7.3	4.2	6.9	3.9	6.7	4.1	6.8
5	5.4	7.9	4.8	7.5	4.5	7.1	4.7	7.4
10	5.7	8.1	5.1	7.7	4.7	7.4	5.0	7.6
20	6.0	8.3	5.3	7.8	4.9	7.5	5.3	7.8
50	6.4	8.7	5.6	8.1	5.2	7.8	5.6	8.1
100	6.7	8.9	5.9	8.3	5.4	7.9	5.8	8.2
200	7.0	9.0	6.1	8.4	5.6	8.1	6.0	8.3
500	7.4	9.2	6.4	8.7	5.9	8.3	6.3	8.6
1000	7.7	9.4	6.7	8.9	6.2	8.5	6.6	8.8

5. JOINT PROBABILITY OF LARGE WAVES AND HIGH WATER LEVELS

Flood risk and potential for damage to coastal structures tends to be associated with times when waves occur in conjunction with unusually high water levels. The joint probability of the simultaneous occurrence of large waves and high water levels is therefore of interest.

The largest waves come from the north, north-east, and east. The largest surges tend to be associated with winds from the north-west and north. Therefore, broadly northerly sea conditions are likely to be the worst case for potential impacts at the coast. This includes most of the largest waves, more of the highest water levels than other wave direction sectors, and a significant dependence between the two. The joint probability assessment is therefore based on all sectors combined, but in the knowledge that such conditions are likely to come from the north.

Section 3.5.3 of CIRIA (1996) provides a method of combining extreme water level predictions with extreme wave predictions in order to derive overall extreme sea conditions with given joint return periods. The necessary 'correlation factor' to be used in CIRIA (1996) was estimated from the results of a more rigorous analysis undertaken previously for nearby Dowsing. The results are listed in Tables 5.1-5.4 for Overstrand, Trimingham, Mundesley, and Bacton, respectively.

Table 5.1 Combinations of large waves and high water levels at Overstrand with given joint return periods

Joint return period (years)	Water levels		Wave conditions		
	Return period (years)	Actual level (mOD)	Return period (years)	H_s (m)	T_m (s)
1	0.03	2.50	1	4.6	7.3
	0.05	2.62	0.6	4.3	7.1
	0.1	2.76	0.3	3.9	6.7
	0.2	2.86	0.15	3.6	6.5
	0.5	2.98	0.06	3.2	6.1
	1	3.08	0.03	2.9	5.8
10	0.08	2.72	10	5.7	8.1
	0.2	2.86	4	5.3	7.8
	0.5	2.98	1.6	4.9	7.5
	1	3.08	0.8	4.5	7.2
	2	3.25	0.4	4.1	6.9
	5	3.44	0.16	3.6	6.5
	10	3.61	0.08	3.3	6.2
100	0.2	2.86	100	6.7	8.8
	0.5	2.98	40	6.3	8.5
	1	3.08	20	6.0	8.3
	2	3.25	10	5.7	8.1
	5	3.44	4	5.3	7.8
	10	3.61	2	5.0	7.6
	20	3.76	1	4.6	7.3
	50	3.95	0.4	4.1	6.9
	100	4.16	0.2	3.7	6.6
1000	0.5	2.98	1000	7.7	9.4
	1	3.08	500	7.4	9.2
	2	3.25	250	7.1	9.0
	5	3.44	100	6.7	8.8
	10	3.61	50	6.4	8.6
	20	3.76	25	6.1	8.4
	50	3.95	10	5.7	8.1
	100	4.16	5	5.4	7.9
	200	4.31	2.5	5.0	7.6
	500	4.49	1	4.6	7.3
	1000	4.67	0.5	4.2	7.0

Note 1: Consider *every* combination as a potential worst case for any given return period. Each one is expected to be equalled or exceeded once, on average, in each return period.
Note 2: Add 6mm/yr (MAFF, 1999) for future sea level rise, after 2002, where appropriate.
Note 3: To convert from OD to CD at Cromer, add 2.75m to water levels.
Note 4: Check for local wave height depth limitation where appropriate.

Table 5.2 Combinations of large waves and high water levels at Trimingham with given joint return periods

Joint return period (years)	Water levels		Wave conditions		
	Return period (years)	Actual level (mOD)	Return period (years)	H_s (m)	T_m (s)
1	0.03	2.41	1	4.2	6.9
	0.05	2.53	0.6	3.9	6.7
	0.1	2.67	0.3	3.6	6.5
	0.2	2.77	0.15	3.4	6.3
	0.5	2.89	0.06	2.9	5.8
	1	2.99	0.03	2.6	5.5
10	0.08	2.63	10	5.1	7.7
	0.2	2.77	4	4.7	7.4
	0.5	2.89	1.6	4.4	7.2
	1	2.99	0.8	4.1	6.8
	2	3.16	0.4	3.8	6.6
	5	3.35	0.16	3.4	6.3
	10	3.52	0.08	3.0	5.9
100	0.2	2.77	100	5.9	8.3
	0.5	2.89	40	5.5	8.0
	1	2.99	20	5.3	7.9
	2	3.16	10	5.1	7.7
	5	3.35	4	4.7	7.4
	10	3.52	2	4.5	7.1
	20	3.67	1	4.2	6.9
	50	3.86	0.4	3.8	6.6
	100	4.07	0.2	3.5	6.4
1000	0.5	2.89	1000	6.7	8.9
	1	2.99	500	6.4	8.7
	2	3.16	250	6.2	8.5
	5	3.35	100	5.9	8.3
	10	3.52	50	5.6	8.1
	20	3.67	25	5.4	7.9
	50	3.86	10	5.1	7.7
	100	4.07	5	4.8	7.5
	200	4.22	2.5	4.5	7.1
	500	4.40	1	4.2	6.9
	1000	4.58	0.5	3.9	6.7

Note 1: Consider *every* combination as a potential worst case for any given return period. Each one is expected to be equalled or exceeded once, on average, in each return period.
Note 2: Add 6mm/yr (MAFF, 1999) for future sea level rise, after 2002, where appropriate.
Note 3: To convert from OD to CD at Cromer, add 2.75m to water levels.
Note 4: Check for local wave height depth limitation where appropriate.

Table 5.3 Combinations of large waves and high water levels at Mundesley with given joint return periods

Joint return period (years)	Water levels		Wave conditions		
	Return period (years)	Actual level (mOD)	Return period (years)	H_s (m)	T_m (s)
1	0.03	2.27	1	3.9	6.7
	0.05	2.40	0.6	3.7	6.5
	0.1	2.54	0.3	3.5	6.3
	0.2	2.64	0.15	3.3	6.2
	0.5	2.76	0.06	2.9	5.8
	1	2.86	0.03	2.6	5.5
10	0.08	2.51	10	4.7	7.4
	0.2	2.64	4	4.4	7.1
	0.5	2.76	1.6	4.1	6.9
	1	2.86	0.8	3.8	6.6
	2	3.03	0.4	3.6	6.4
	5	3.22	0.16	3.3	6.2
	10	3.39	0.08	3.0	5.9
100	0.2	2.64	100	5.4	7.9
	0.5	2.76	40	5.1	7.7
	1	2.86	20	4.9	7.5
	2	3.03	10	4.7	7.4
	5	3.22	4	4.4	7.1
	10	3.39	2	4.2	6.9
	20	3.55	1	3.9	6.7
	50	3.73	0.4	3.6	6.4
	100	3.94	0.2	3.4	6.3
1000	0.5	2.76	1000	6.2	8.5
	1	2.86	500	5.9	8.3
	2	3.03	250	5.7	8.1
	5	3.22	100	5.4	7.9
	10	3.39	50	5.2	7.8
	20	3.55	25	5.0	7.6
	50	3.73	10	4.7	7.4
	100	3.94	5	4.5	7.2
	200	4.09	2.5	4.2	6.9
	500	4.27	1	3.9	6.7
	1000	4.43	0.5	3.7	6.5

Note 1: Consider *every* combination as a potential worst case for any given return period. Each one is expected to be equalled or exceeded once, on average, in each return period.
Note 2: Add 6mm/yr (MAFF, 1999) for future sea level rise, after 2002, where appropriate.
Note 3: To convert from OD to CD at Cromer, add 2.75m to water levels.
Note 4: Check for local wave height depth limitation where appropriate.

Table 5.4 Combinations of large waves and high water levels at Bacton with given joint return periods

Joint return period (years)	Water levels		Wave conditions		
	Return period (years)	Actual level (mOD)	Return period (years)	H_s (m)	T_m (s)
1	0.03	2.13	1	4.1	6.8
	0.05	2.25	0.6	3.8	6.6
	0.1	2.39	0.3	3.5	6.4
	0.2	2.49	0.15	3.3	6.2
	0.5	2.61	0.06	2.9	5.8
	1	2.71	0.03	2.6	5.5
10	0.08	2.35	10	5.0	7.6
	0.2	2.49	4	4.6	7.3
	0.5	2.61	1.6	4.3	7.1
	1	2.71	0.8	4.0	6.7
	2	2.88	0.4	3.7	6.5
	5	3.07	0.16	3.3	6.2
	10	3.24	0.08	3.0	5.9
100	0.2	2.49	100	5.8	8.2
	0.5	2.61	40	5.5	8.0
	1	2.71	20	5.3	7.8
	2	2.88	10	5.0	7.6
	5	3.07	4	4.6	7.3
	10	3.24	2	4.4	7.0
	20	3.39	1	4.1	6.8
	50	3.58	0.4	3.7	6.5
	100	3.79	0.2	3.4	6.3
1000	0.5	2.61	1000	6.6	8.8
	1	2.71	500	6.3	8.6
	2	2.88	250	6.1	8.4
	5	3.07	100	5.8	8.2
	10	3.24	50	5.6	8.1
	20	3.39	25	5.4	7.9
	50	3.58	10	5.0	7.6
	100	3.79	5	4.7	7.4
	200	3.94	2.5	4.4	7.0
	500	4.12	1	4.1	6.8
	1000	4.37	0.5	3.8	6.6

Note 1: Consider *every* combination as a potential worst case for any given return period. Each one is expected to be equalled or exceeded once, on average, in each return period.
Note 2: Add 6mm/yr (MAFF, 1999) for future sea level rise, after 2002, where appropriate.
Note 3: To convert from OD to CD at Cromer, add 2.75m to water levels.
Note 4: Check for local wave height depth limitation where appropriate.

6. PREPARATION OF TIME SERIES DATA FOR USE IN CLIFF MODELLING

The cliff-modelling element of this project needed very long site-specific sequences of wave and tidal data as input. The particular requirements were for the wave and tidal data to:

- be transformed to each of the nearshore positions of interest, namely Overstrand, Trimingham, Mundesley and Bacton;
- be extended to a 1000 year sequence, but with greater variability amongst the highest values than seen within the source data;
- retain proper seasonality (month by month variability), sequencing (hour by hour variability) and dependence between parameters (wave height, wave period, wave direction, water level).

The client provided 10 years of sequential water level data measured at Cromer for use within this study. As nearly 20% of the data was missing, to obtain as many complete calendar months as possible, up to four days of missing data within any particular month were patched using astronomical tidal predictions. This left the complete months of hourly tidal data as given in Table 6.1. These 97 complete months of good data were transformed (i.e. tidal ranges reduced) to Overstrand, Trimingham, Mundesley, and Bacton; and the data was matched on an hourly basis with the corresponding nearshore wave predictions for the sites.

Table 6.1 Complete months of data used in the 10-year series

Year	J	F	M	A	M	J	J	A	S	O	N	D
1991				X	X	X	X	X	X	X	X	X
1992	X	X	X									
1993	X	X	X	X	X	X	X	X	X	X	X	X
1994	X	X	X							X	X	X
1995	X	X	X	X	X	X	X	X	X	X	X	X
1996	X	X	X	X	X	X	X	X			X	X
1997	X	X	X	X	X	X	X	X	X	X	X	X
1998	X	X	X	X	X	X	X	X	X	X	X	X
1999	X	X	X	X	X	X	X					X
2000	X	X	X	X	X	X	X		X		X	X
2001	X	X	X									

The 1000-year simulation is a random generation of a full 12000-month sequence from the available 97 complete months of good data. The simulation retains the seasonality by selecting for a generated January, an available January, and so on.

A random variability factor is applied to keep a good correlation between the original and the simulated data, whilst also taking into account the predicted extreme values of the wave height and the water level for each studied area. To match the predicted extreme values, a factor is calculated to set the spreading range of the values above a given threshold. When the wave height or the water level is greater than its respective threshold, a random spreading is applied within the spreading range. This range is set from the spreading factor but also from the difference between the threshold and the wave height or the difference between the threshold and the water level.

To ensure the quality of the reproduced data, a comparison of the high and extreme values of wave height (H_s) and water level was made between the original 10-year and the derived 1000-year data series. This exercise revealed a good correlation of the distribution of wave height and indicated that the extreme values match with those predicted earlier in this report.

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