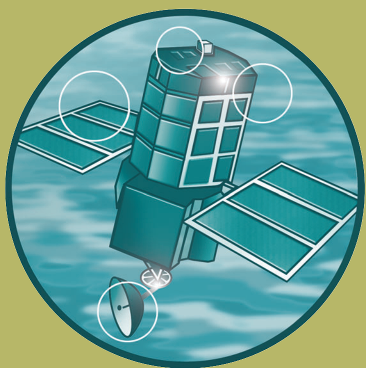
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Development of estuary morphological models

Annex A1: SWAN modelling of Liverpool Bay including Dee, Mersey and Ribble Estuaries

Judith Wolf, August 2007

R&D Project Record FD2107/PR



Environment Agency

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SWAN modelling of Liverpool Bay including Dee, Mersey and Ribble Estuaries

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Introduction

As part of the FD2107 project POL was required to assess the effect of waves on the morphology of the Mersey, Dee and Ribble estuaries. The role of waves in sediment transport is often in mobilising sediment in the nearshore zone, which can then be transported by tidal currents, and also in coastal erosion and flooding during storms which may cause catastrophic changes if coastal defences are overtopped. Waves in shallow water are strongly controlled by the water level as well as the wind forcing. Here we use data from the POL Coastal Observatory and the SWAN wave model to investigate the occurrence of typical and extreme wave conditions in Liverpool Bay and the adjacent estuaries and assess areas which may be prone to flooding due to waves in combination with high water levels. The following tasks were identified:

1. Review existing data on wind and waves in Liverpool Bay.
2. Set up SWAN on the extended Liverpool Bay model including the Dee, Mersey and Ribble estuaries. Select model physics options. Test SWAN version 40.31 versus latest 40.51. Select frequency and direction resolution.
3. Plan runs: (a) select forcing scenarios on the basis of wind climate (b) choose output parameters and locations relevant to flooding in the estuaries of interest c) investigate water levels due to tides and surges.
4. Carry out present-day wave climate runs, including 50%, 90%, 95%, 99% and an extreme wave height case e.g. 1 in 100 year event.
5. Examine a climate change scenario by means of an increase in sea level and ‘storminess’ :- wind-speed + 10%, water level + 25cm.

Present-Day Wind and Wave Climate

The area of interest is Liverpool Bay in the northern Irish Sea and the Mersey, Dee and Ribble estuaries in particular. The location of the area to be modelled is shown in Figure 1, with further detail in Figure 11. Winds are being recorded by the automatic weather station on Hilbre Island as part of the POL Coastal Observatory (http://cobs.pol.ac.uk/). Waves are being monitored by a Directional Waverider in 22m water depth in Liverpool Bay which is part of the WaveNet network and by a POL Triaxys wave buoy in the Hilbre Channel adjacent to Hilbre Island in 10-15m water.

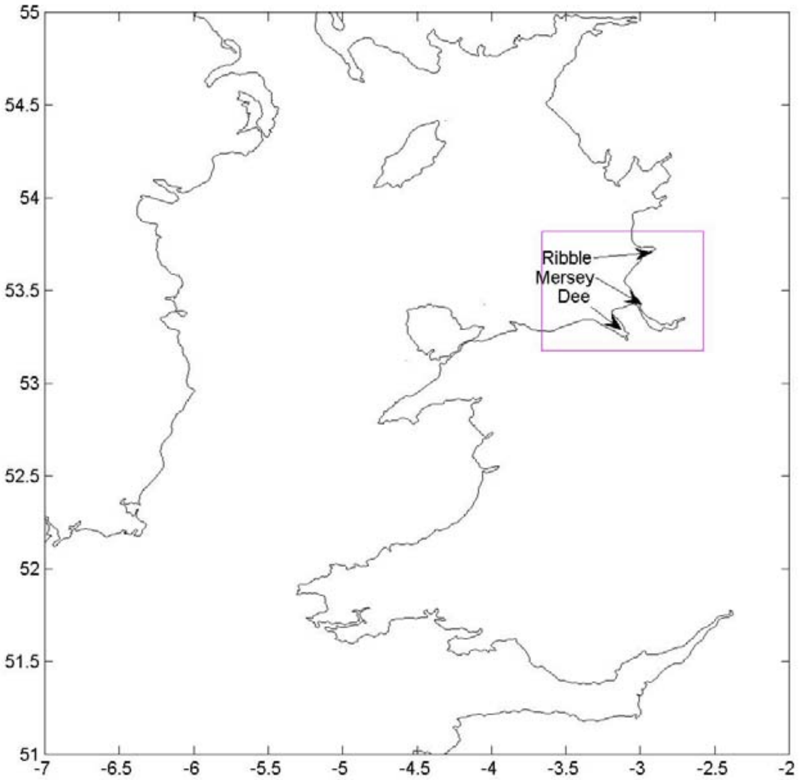


Figure 1: Map of Irish Sea showing location of estuaries of Dee, Mersey and Ribble and box enclosing modelled area corresponding to Liverpool Bay

Waves in Liverpool Bay are mainly locally-generated, as swell does not easily propagate from the North Atlantic into this part of the Irish Sea. Therefore it is assumed that the waves of interest are fetch-limited wind-sea, closely related to the local wind conditions. Previous work on wind and waves observed at the Mersey Bar light ship (at almost the same location as the present WaveNet buoy) was done by Hedges et al. (1991) and Battjes (1972). They used 7 years of wind data from 1964 to 1971 and 1 year of wave data from 1965-66, at 3-hour intervals.

Here we examine 1 year's data for wind and waves from May 2004-April 2005 from the Hilbre Island weather station and WaveNet buoy and derive some statistics. The wind data are shown as a wind rose in Figure 2, which illustrates their directional distribution. The winds display a bimodal distribution in terms of direction with the strongest and most frequent winds from the west but a secondary peak from the SE.

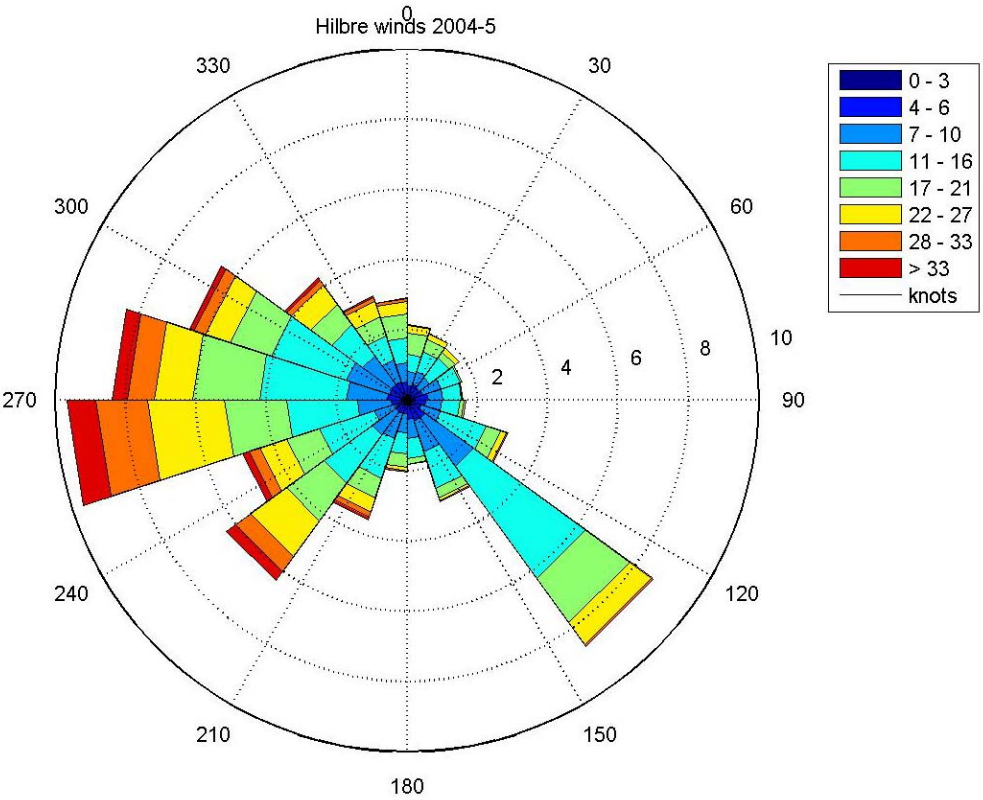


Figure 2: Wind rose for 2004-5 at Hilbre Island

In figure 3 it can be seen that the wind-speed data are well-fitted by a Rayleigh probability distribution function (pdf). This allows the probability distribution to be described by a single parameter, derived from the variance of the data. The Rayleigh distribution for the WNW and SE wind cases are also shown: these being the main directions producing the dominant peaks in wave height. Although it would be possible to extrapolate the extreme tail of the distribution to obtain longer return periods, it may be misleading to go beyond the 1 year of data examined. Therefore we restrict the quantitative analysis of extremes to examining the percentiles of the distribution. The median (50%) and 90%, 95% and 99% wind-speeds are selected for WNW and SE winds respectively. The maximum observed 10-minute wind during this period was 29.3m/s, whereas the maximum 12-hour mean value was 22m/s (Figure 5), both occurring on 8 Jan 2005.

The cumulative percentiles for WNW winds are:

99%: 19.9m/s, 95%: 17.0m/s, 90%: 15.1m/s, median: 8.26m/s

The cumulative percentiles for SE winds are:

99%: 13.9m/s, 95%: 11.6m/s, 90%: 10.2m/s, median: 5.98m/s The maximum observed 10-minute wind from SE was 18.6m/s,

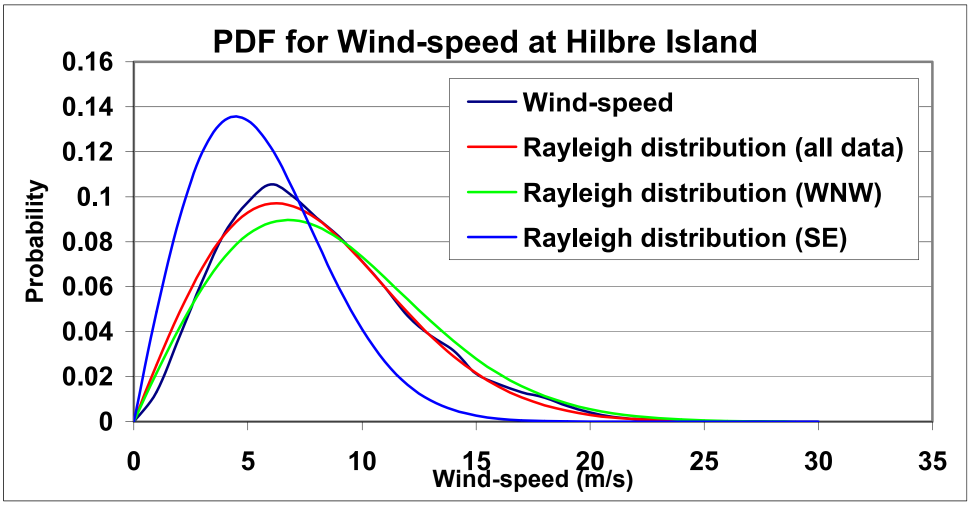


Figure 3: Probability distribution function for winds at Hilbre Island

Wave climate can also be presented as a compass rose, see Figure 4. As may be expected the largest waves are from just north of west, which has the longest fetch for locally-generated waves (up to 250km, see Figure 1), with some wave energy from SE.

The pdf for wave height is better fitted by a 2-parameter Weibull distribution function than the Rayleigh distribution (Figure 5). The Weibull distribution is a generalisation of the Rayleigh distribution, with shape and scale parameters, α and β. In this case α = 1.439 (±0.017) and β = 1.064 (±0.012) where bracketed values are the 95% confidence limits. These values are higher than those derived by Battjes (1972) from 1965-6 data (α = 1.06, β = 0.62). With only 1 year of data in each case this suggests that there is a lot of interannual variability. Some of this variability may be correlated with the North Atlantic Oscillation index which has been shown to correlate with the strength of the westerly wind regime for western parts of the UK (Tsimplis et al., 2005; Wolf and Woolf, 2006). This needs further investigation. Ideally, we need longer time series of offshore data to characterise the wind and wave climate.

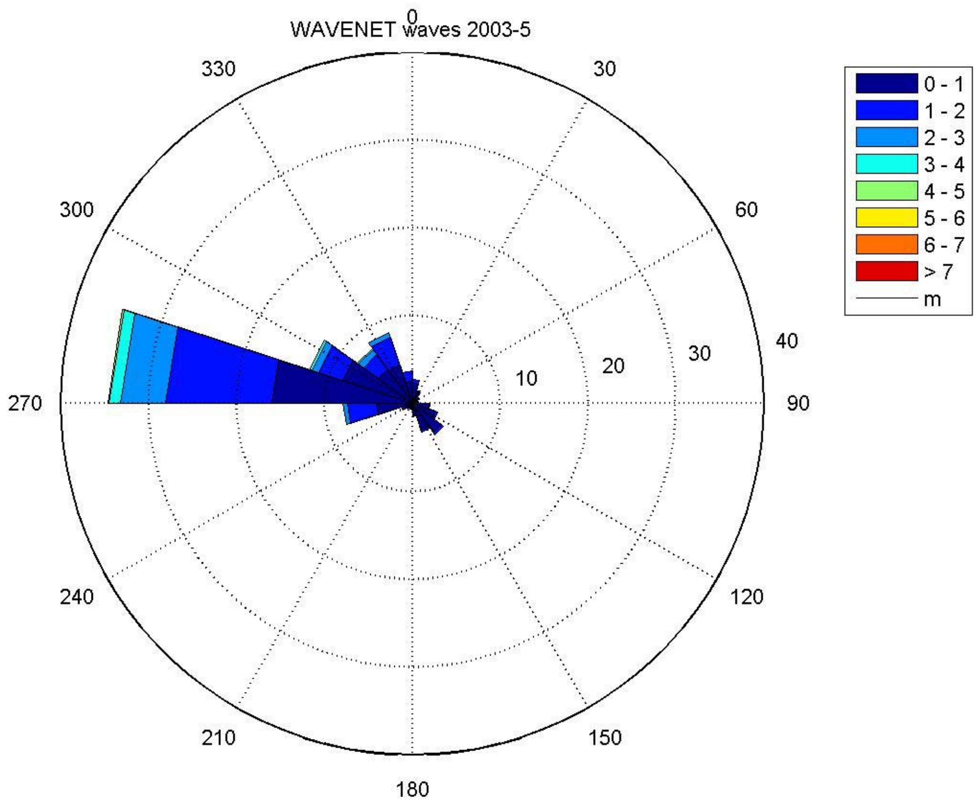


Figure 4: Wave rose for Wavenet buoy in Liverpool Bay

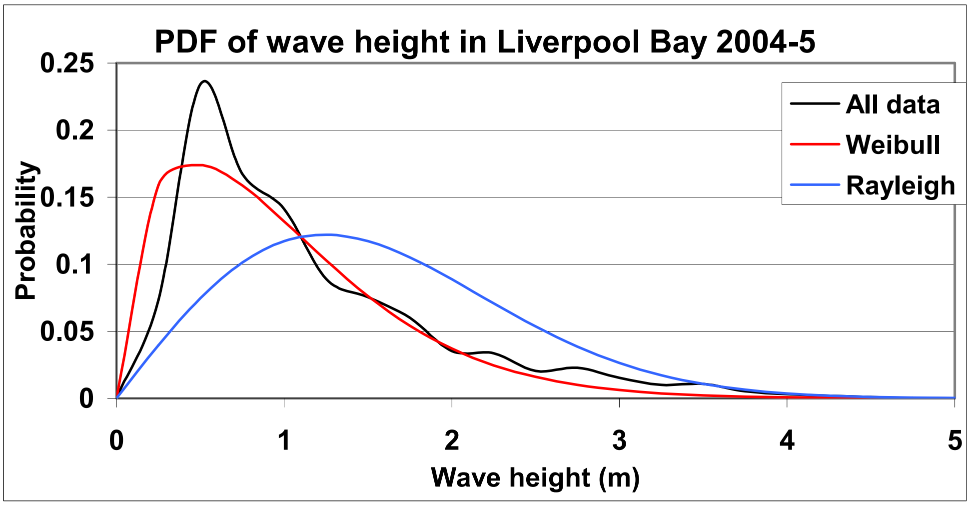


Figure 5: Probability distribution function for waves in Liverpool Bay

The wave statistics can also be presented as scatter plots (Figure 6) which illustrate the directional distribution and highlight the fact that for low wave height there can be some swell, as evidenced by large peak wave period (Tp) and a large discrepancy between the mean wave period (Tm02, also known as Tz) and Tp.

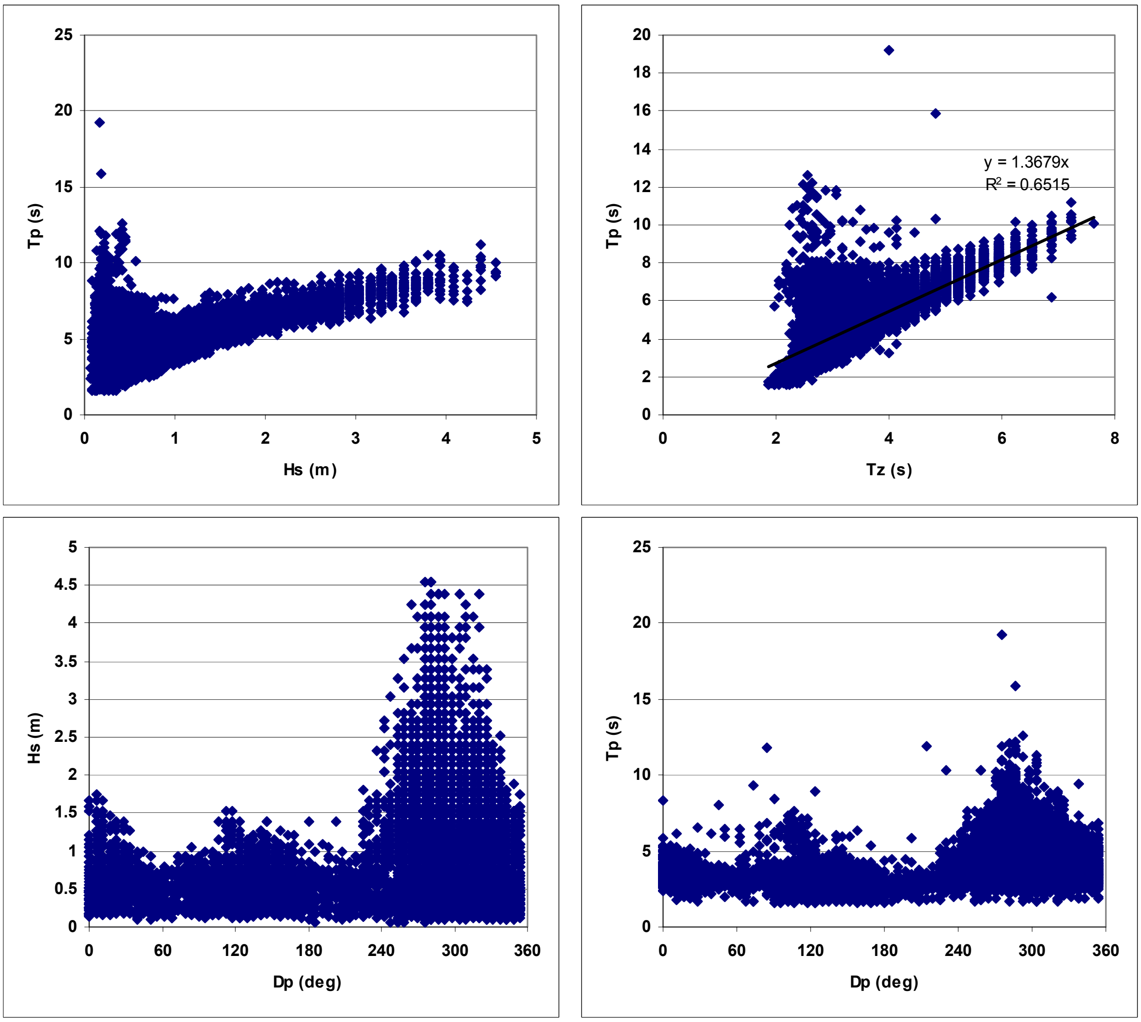


Figure 6: Wave parameter scatter plots

It has been assumed that the local wave generation is fetch-limited but it is worth examining the minimum wind duration necessary for the waves to reach their fetch-limited growth in Liverpool Bay. From Figure 3-23 in the Shore Protection Manual Volume 1 (U.S. Army Coastal Engineering Research Centre, 1984), it appears that for a fetch of 250km the minimum wind duration is about 12 hours for winds exceeding 20m/s. It increases with reducing wind speed up to 16 hours for 10m/s winds, but a fully-arisen sea is reached for 8m/s by 12 hours i.e. the waves are no longer fetch-limited. Thus 12 hours is a reasonable duration for waves to reach their full potential. Figure 7 plots the 12-hour vector-averaged wind-speed. It may be seen that the 12-hour mean wind-speed exceeded 20m/s on 2 occasions during the year. Winds at Hilbre Island are likely to be affected by the reduction in wind over land, so that winds at the WaveNet buoy location would be expected to be somewhat larger.

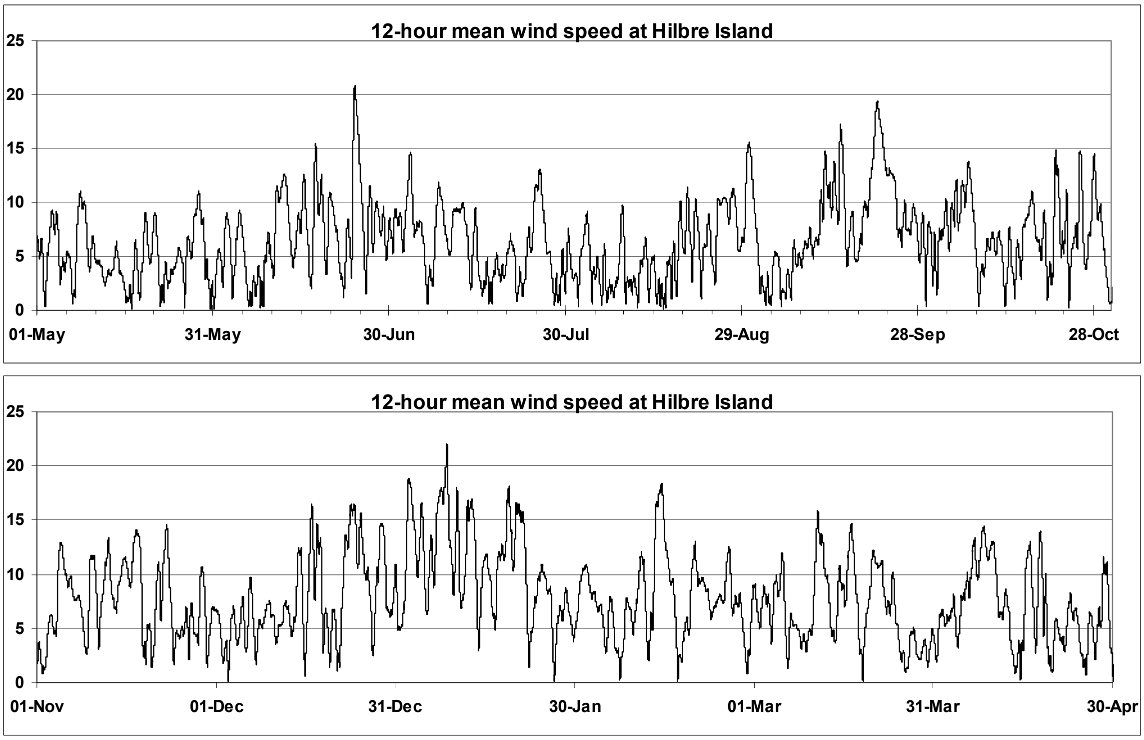


Figure 7: 12-hour mean wind-speed from Hilbre Island

Water level

As already discussed, the most damaging waves will be those occurring on high water levels. The water level is composed of mean sea level plus tide and surge. We therefore examine the probability distribution of water levels for the Liverpool Bay area. Tide and surge effects are not totally independent as there are interactions between them, and the maximum surge will not necessarily fall on high water. Joint probability of surge and tide is discussed e.g. in Pugh (2004), where it is also pointed out (p.186) that the most probable (frequently-occurring) water levels are mean high water neap (MHWN) and mean low water neap (MLWN). Chart datum, MHWN, mean high water springs (MHWS) and highest astronomical tide (HAT) data are available for Liverpool and other locations within the area. Data were compared for Rhyl, Mostyn, Hilbre Island, Birkenhead, Liverpool, Southport, Blackpool, Chester and Fiddlers Ferry. These showed some variation in high water levels, especially higher up the Dee and Mersey estuaries at Chester and Fiddlers Ferry but in the outer estuary were quite similar (~2-3% variation from mean) so the total water level was assumed uniform over the model area. The tidal phase is almost coincident so this is a reasonable assumption. The average for the stations excluding Chester and Fiddlers

Ferry were used as follows: chart datum =-4.93m ODN, MHWN = 2.2m ODN, MHWS = 4.1m ODN, HAT = 5.3m ODN, where mean sea level is assumed to be equivalent to Ordnance Datum Newlyn (ODN).

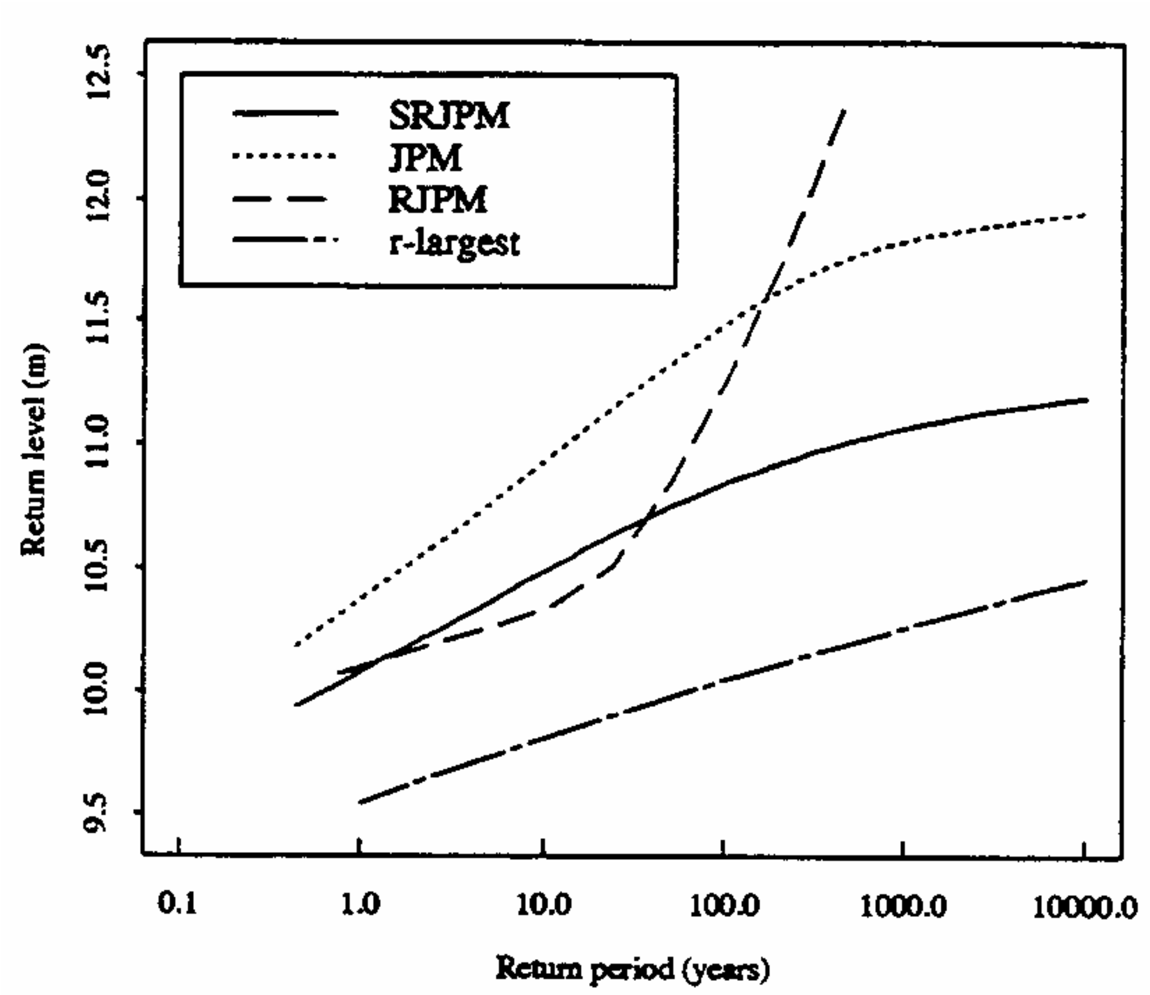


Figure 8: Extreme water levels at Liverpool, from Dixon and Tawn (1995)

Extreme water levels at Liverpool were investigated by Dixon and Tawn (1995) using various joint probability methods (see Figure 8), viz. Joint Probability Method (JPM), Revised Joint Probability Method (RJPM) and Spatial Revised Joint Probability Method (SRJPM). Assuming the SRJPM gives the most correct results we can extract the 1 in 100 years extreme level for Liverpool as about 10.8m (relative to chart datum) i.e. 5.9m ODN.

Flood Risk

Coastal flooding includes the combined effects of sea level and waves. If the sea level is increased due to high tide or tide plus surge waves can impact further inland and are more likely to overtop any sea defences. In very shallow water wave height is closely controlled by water depth so if the water level is elevated the wave will be larger. Surge and wave events are likely to be generated by the same storm event. Since these effects are not independent, ideally the joint probability of a certain water level and wave height occurring should be investigated. The standard methods used are described in the wave overtopping manual (HR Wallingford Ltd., 1999).

The Environment Agency has produced maps of flood risk and defences for UK coast. Recent (<5 years) defences and some older defences are included (http://maps.environment-agency.gov.uk/wiyby/mapController). The map for the Liverpool Bay area is shown in Figure 9. Looking in more detail at sub-areas, shows the flood defences as well as the flood risk areas, although not all defences are marked (Figure 10). The risk areas include the Ribble estuary, especially around Southport, the inner Dee and Mersey estuaries and part of the North Wales coast around Rhyl and Point of Ayr. Potential flooding is also identified along the North Wirral coast and Formby/Sefton coast.

The review by Reis et al (2005) includes various empirical formulae e.g. Owen (1980), semi-empirical (Hedges and Reis, 1998) and numerical models of overtopping e.g. AMAZON (Hu, 2000). The main inputs to empirical overtopping models are wave height and period and information on the seawall slope and freeboard. The latter information is not included here as it could not be represented at the present model resolution (185m) and the spectral wave model cannot reproduce actual wave time series. It is possible to use SWAN output to drive an overtopping model e.g. Sutherland and Wolf (2001). For the present application, however, maps of wave height, period and setup are produced from the SWAN model, with point output at selected points in the model, which are taken to represent the wave conditions in the indicated flood risk areas.

Figure 9: EA Flood Risk Map for Liverpool Bay area

Selected water levels can be used with different winds in SWAN to generate various wave scenarios. It is likely that flooding will only occur when the water level due to tide and surge is also high although this should be investigated further. Sutherland and Wolf (2001) discussed the combined probability of waves and water levels and their likely changes under a future climate scenario when sea levels are likely to increase. Case studies are selected here to cover a range of 'typical' and extreme events, using moderate and high water levels and winds.

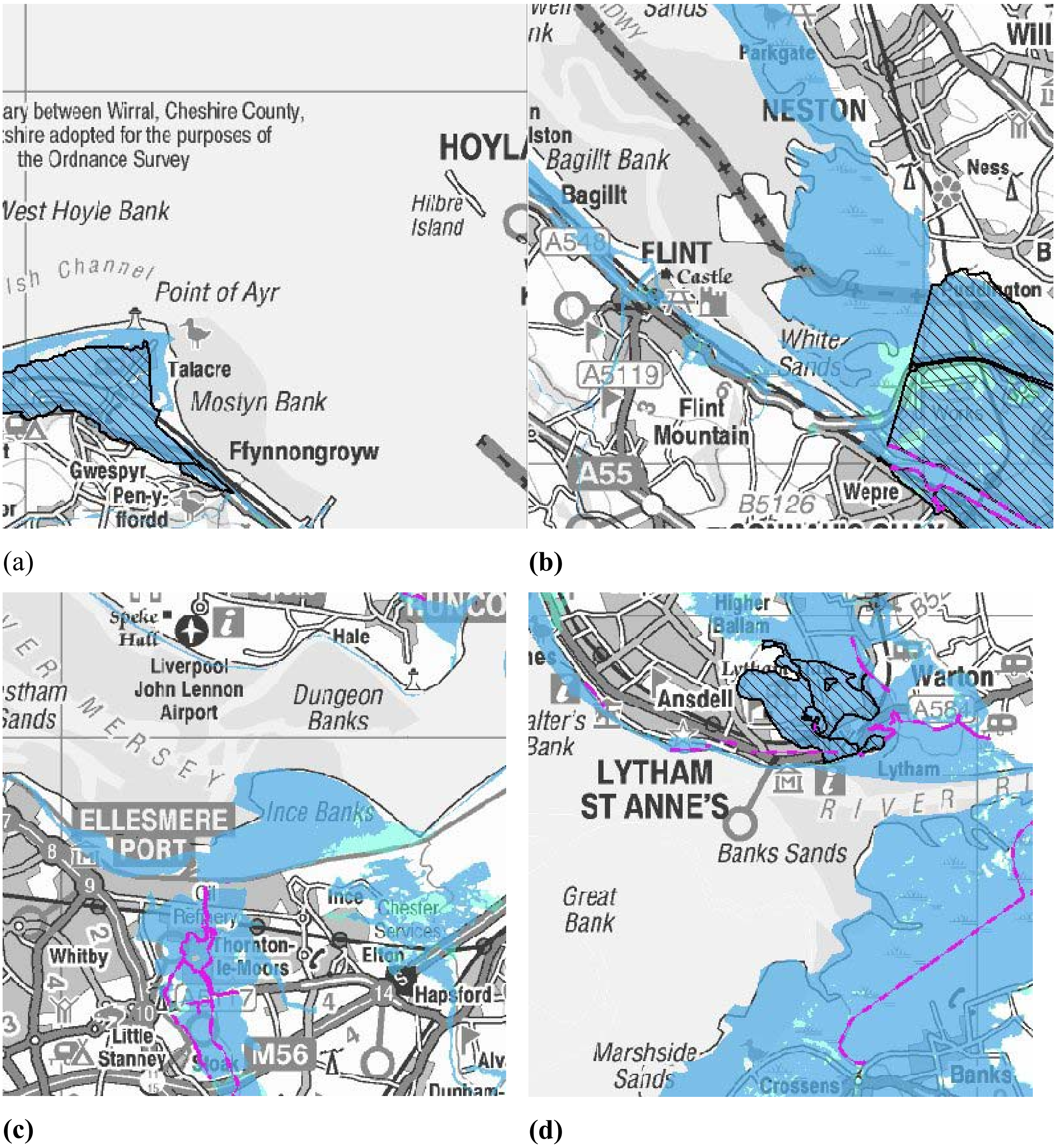


Figure 10: Flood risk and defences on the Dee, Mersey and Ribble (extracts from EA flood risk maps) (a) Outer Dee Estuary (b) Inner Dee Estuary (c) Part of the Mersey Estuary (d) Ribble Estuary. Blue shading indicates areas at risk of flooding, purple lines indicate flood defences

Sediment transport

In order to examine the magnitude of sediment transport due to waves, the most important parameter is the energy dissipation caused by the bottom friction stress due to waves. This can be generated from the SWAN model. It is assumed that the mobile sediment in the outer estuary is medium sand with grain size around 200μm (threshold bed shear stress ~ 0.2Nm^{-2} from Soulsby, 1997) and suspended sediment with silt-clay consistency is ignored from the point of view of wave transport. This is a highly energetic tidal environment and waves are not necessary to mobilise sediment in the outer estuaries but may modify the sediment erosion at times of storms. Within the estuaries waves can play a part in eroding the edges of salt-marsh even with short-fetch locally generated waves. Details of these processes are not examined further here.

SWAN Wave Model

The SWAN model is a 3rd-generation spectral wave model (Booij et al., 1999; Ris et al., 1999), which accounts for the effects of wave generation by wind, dissipation of energy by deep-water breaking (white-capping), shallow water breaking and bottom friction and the redistribution of energy by nonlinear wave-wave interactions. A recent review of the state of the art of wave modelling is given in Cavaleri et al. 2007). SWAN was developed specifically for shallow water areas where high spatial resolution is required and has been used extensively for scientific and coastal engineering applications. The latest release of SWAN (http://vlm089.citg.tudelft.nl/swan/index.htm) is version 40.51. Previous runs of the Liverpool Bay model using SWAN at POL were done with version 40.31 (Wolf and Wakelin, 2003; 2004) so an initial test was done to see if the new version produced different results. Slight differences were obtained for wave parameters. However major differences in the setup were observed. It is assumed that version 40.51 is more correct and therefore the results from this are presented below. (Note – no such differences were observed in previous wave setup calculations with version 40.31, 40.41 and 40.51 but these were over much simpler bathymetry.)

A gridded bathymetric dataset was obtained from Andrew Lane at POL on 1/600° by 1/400° latitude-longitude grid. This corresponds to approximately 1/10 of a nautical mile (~185m). Since wave setup was required as an output parameter it was necessary to run SWAN on a Cartesian grid (see SWAN manual, available from the web site as above) so the data were interpolated onto a 185m by 185m grid over the same area. The extent of the model was then (in Ordnance Survey grid coordinates) as given in Table 1 and shown in Figure 11.

SW corner (OS coords)	NE corner (OS coords)	dx, dy (m)	NX	NY
290481, 365998	362076, 435928	185, 185	387	378

Table 1: Grid parameters for Liverpool Bay model on Cartesian grid

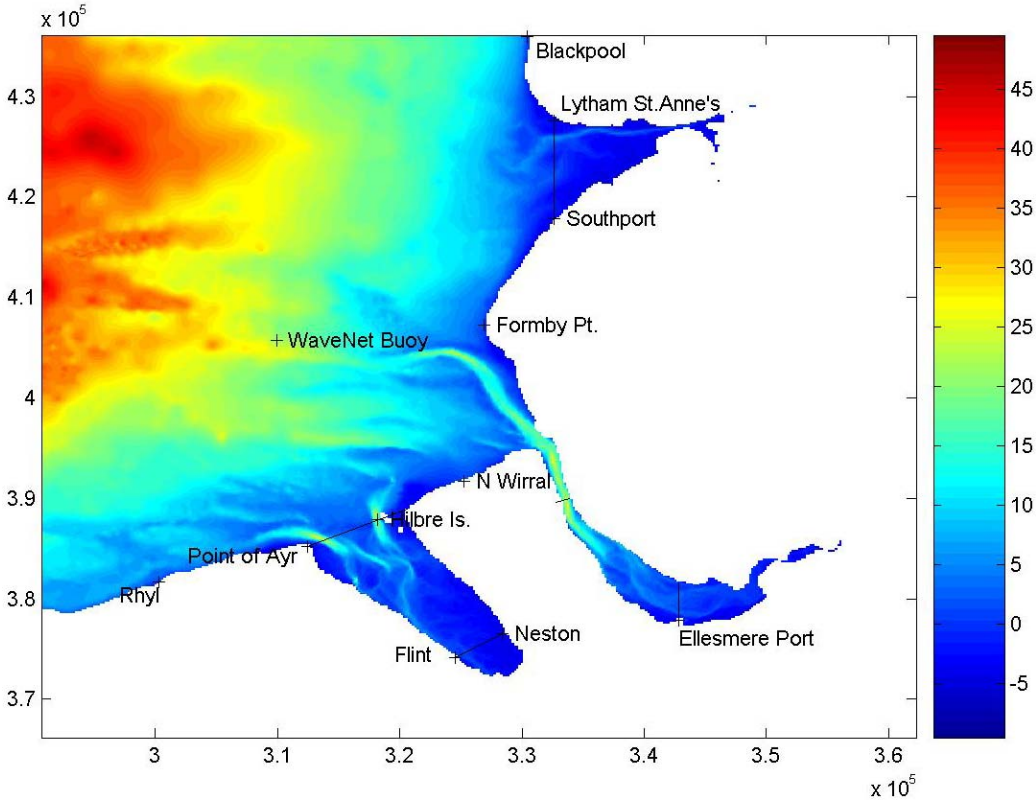


Figure 11: Liverpool Bay bathymetry on a Cartesian grid (OS grid) showing locations of output coastal points and sections, plus location of wave observations (WaveNet Buoy and Hilbre Island)

	Place	Easting (m)	Northing (m)	Depth (m) (ODN)
1	Rhyl	300286	381725	1.02
2	Point of Ayr	312436	385252	-1.77
3	Hilbre Island	318200	387840	11.5
4	Flint	324558	374162	-0.38
5	Neston	328385	376565	-3.96
6	N Wirral	325261	391714	1.12
7	Ellesmere Port	342836	377864	-1.24
8	Formby Point	326924	407253	-2.25
9	Southport	332661	417798	-3.51
10	Lytham St. Anne’s	332661	427598	-3.62
11	Blackpool	330440	435928	0.02
12	WaveNet Buoy	309906	405773	21.2

Table 2: Output stations

Output points were selected within flood risk areas, taking the nearest wet point to the coast, as well as at the locations of the wave observations. The locations are shown in Table 2. Results were also generated along cross-sections of the Dee, Mersey and Ribble: line 1 from Point of Ayr to Hilbre Island and West Kirby, line 2 from Flint to Neston, line 3 from Birkenhead to Liverpool, line 4 from Ellesmere Port to Speke and line 5 from Southport to Lytham St. Anne's.

It was decided to use 36 directions and 33 frequencies (logarithmically distributed from 0.05 to 1.03 Hz) for the local scale required. The higher frequencies are mainly needed for low wind speeds. SWAN was run in stationary mode (i.e. no time-stepping, assumes unlimited duration), with depth-limited breaking switched on, no triad interactions and the Madsen bottom friction option.

The offshore boundary wave height and period for the wave model is generated by means of parametric wave modelling following the method of Hurdle and Stive (1989):

$$H_S = 0.25\frac{U_a^{\ 2}}{g}\alpha\sqrt{\tanh(4.3.10^{-5}\,\overline{F}/\alpha^2)},\quad T_P = 8.3\frac{U_a}{g}\beta\sqrt[3]{(\tanh(4.1.10^{-5}\,\overline{F}/\beta^3)}\,, \tag{1}$$

where $\alpha = \tanh(0.6\overline{d}^{\,0.75})$, $\beta = \tanh(0.76\overline{d}^{\,0.375})$. The non-dimensionalised depth and fetch respectively are $\overline{d} = hg/U_a^{\ 2}$, $\overline{F} = Fg/U_a^{\ 2}$ and the effective wind-speed $U_a = 0.71(1.1U_{10})^{1.23}$. Here, F is the fetch in metres, U_{10} is the wind speed at 10m above the sea surface and h is the water depth. This assumes fetch-limited (duration unlimited) wave growth, which is probably reasonable for this area as discussed earlier.

Model validation and wave physics options

Generally, it has been observed that SWAN underestimates the mean wave period (e.g. Rogers et al., 2003). This is an important parameter for wave overtopping and various ways have been suggested to deal with this problem, which is often attributed to incorrect wind-sea/swell dissipation. The SWAN model has various options for 3rdgeneration physics, which represent different parameterisations of the white-capping dissipation term (the least well-understood of the source terms) combined with the wind input term. These have generally been tuned to reproduce standard fetch-limited growth curved. Other investigations e.g. Rogers et al. (2003) and Alves and Banner (2003) have suggested further modifications, but due to time limitations only the options already available in SWAN were tested here. These are: Komen (default), Janssen, the Cumulative Steepness Method (CSM) and Westhuysen. The rationale and technical description of these options are not described in detail here as the information is available through the SWAN web-site.

In order to test these options 2 test cases were selected where observed wave data are available from the WaveNet buoy and Hilbre Island, with wind data from Hilbre Island. Figure 12 shows the observed waves at both stations for a few days in February 2005. The very marked tidal modulation of the observed waves at Hilbre Island can partly be attributed to its location inside the Hoyle Bank, where it is almost isolated at low water from the outer Liverpool Bay area (Wolf et al., 2007) and the effective fetch is much reduced. The maximum observed wave height at high water (HW) on 13 February at Hilbre Island was 2.61m at 02:00 GMT. It was decided to use that HW and the following low water (LW) times for validation of the wave model and to test the physics options.

Option	**Wind speed**		**Water level**	**Liverpool Bay WaveNet buoy**			**Hilbre Island Triaxys buoy**		
	Hour-ly	**24-hr mean**		**Hs (m)**	**Tm02 (s)**	**Tp (s)**	**Hs (m)**	**Tm02 (s)**	**Tp (s)**
Observations	19.3	16.8	HW	**3.67**	**6.24**	**7.91**	**2.61**	**7.07**	**8.00**
Test1 – Komen	16		HW	3.76	5.47	**7.94**	1.85	3.71	7.94
Test2 – Janssen	20		HW	**3.70**	**6.35**	**7.94**	1.86	**3.89**	7.94
Test3 – CSM	25		HW	3.74	5.47	8.70	**2.04**	3.64	7.94
Test4 - Westhuysen	16		HW	3.71	5.72	**7.94**	1.80	3.87	7.94
Observations	17.5	17.4	LW	**3.67**	**6.24**	**8.31**	**0.73**	**2.85**	**3.17**
Test1 – Komen	17		LW	**3.56**	5.18	**7.94**	0.52	1.53	2.39
Test2 – Janssen	20		LW	3.37	**6.11**	**7.94**	**0.62**	**1.84**	2.62
Test3 – CSM	25		LW	3.47	5.13	8.70	0.88	1.89	**2.87**
Test4 - Westhuysen	17		LW	3.53	5.46	**7.94**	0.57	1.66	2.62

Table 3: Comparison of wave model output with observations - HW: 02:00 13 February 2005 =+3.84m ODN), LW: 08:00 13 February 2005 =-3.72m ODN

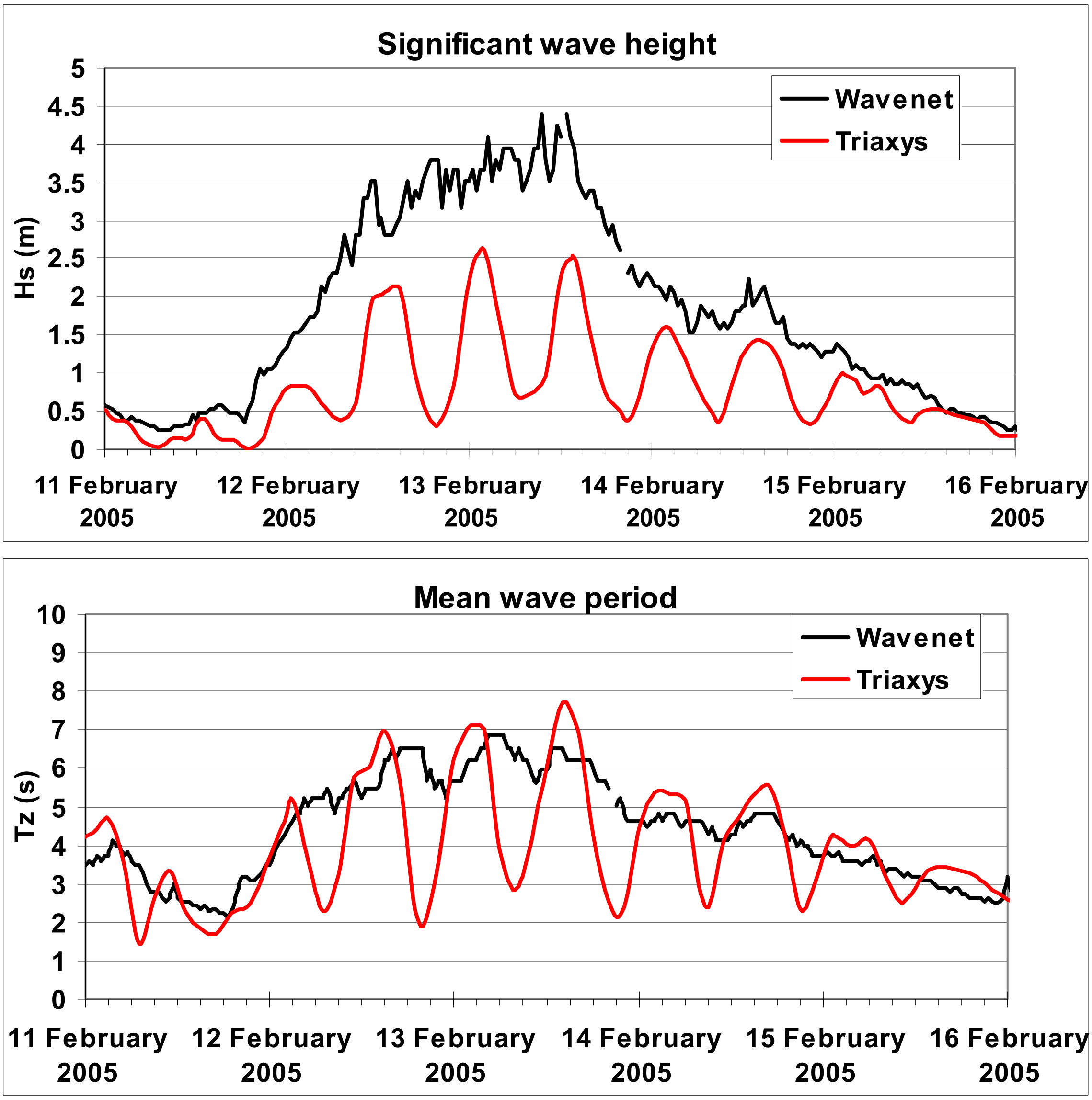


Figure 12: Wave observations 11-16 February 2005

The results, shown in Table 3, are somewhat ambiguous. Best agreement with observed data for each parameter is highlighted in bold. The wind-speed has been adjusted in some cases to bring the wave height results at the outer buoy into better agreement with observations. This may be justified to some extent by arguing that the offshore wind-speed will be higher than that observed at Hilbre Island. However for the default (Komen) case the appropriate wind-speed is more equivalent to the mean over the preceding 24 hours and lower than the nearest hourly observation at Hilbre Island. It will always be difficult to specify the correct effective wind-speed in a stationary model, which is equivalent to forcing by unlimited duration fetch-limited winds. Sometimes the advantage of one choice in the outer model area (WaveNet buoy) is cancelled out at the inner location (Hilbre Island). The Janssen option improves the mean wave period in most cases and therefore this was selected. It does require a higher wind-speed than the Komen option to achieve the same wave height. All the physics options tested here markedly underestimate the mean wave period at Hilbre Island. This suggests too much dissipation of the long wave components in the spectrum in shallow water, which may also be affected by the choice of bottom friction. This has not been investigated further here.

Case Studies

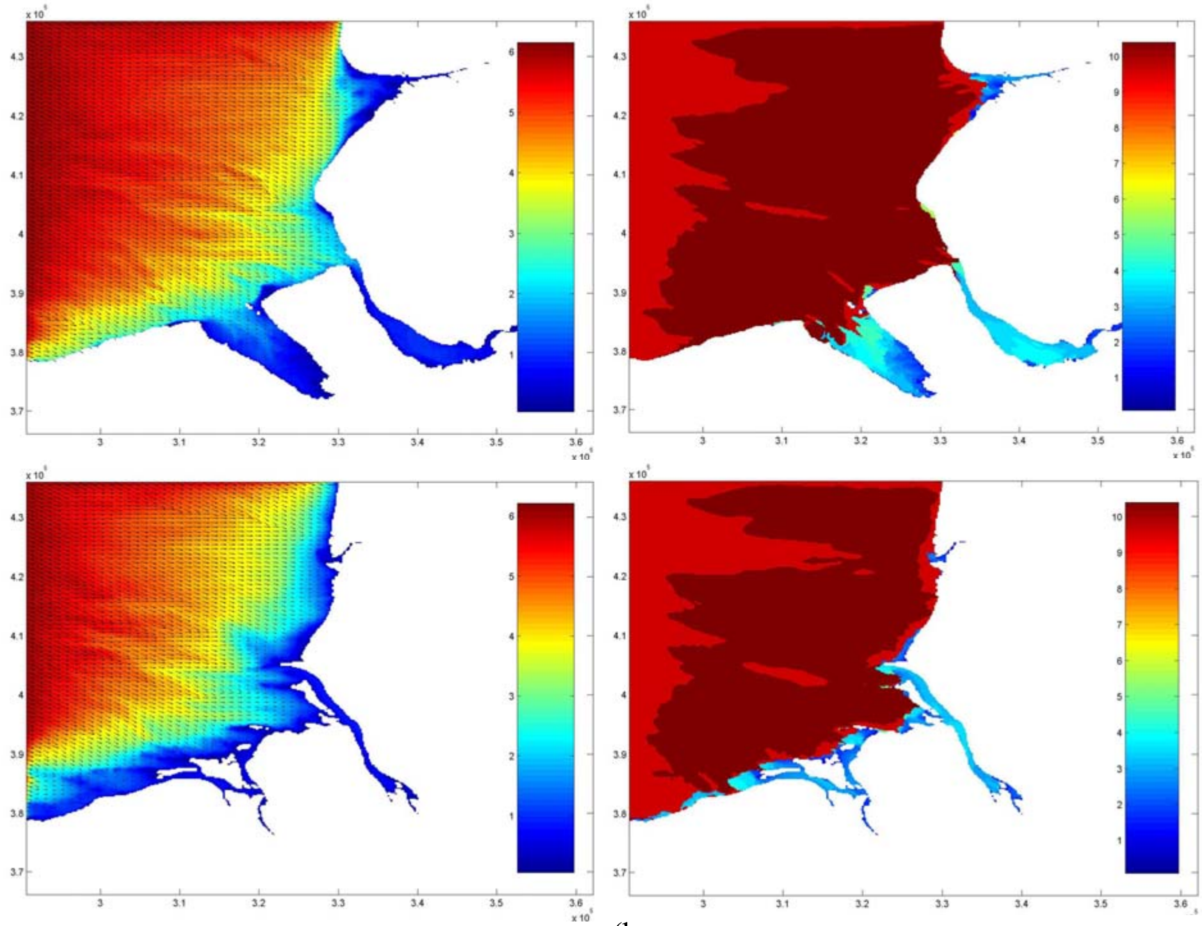
Various combinations of water level and wind speed were run. In each case the wind direction was from WNW. The cases are tabulated in Table 4. TIDE1 and TIDE2 are quite strong winds on a spring tide, HW and LW respectively, for illustration of the effects of water level. CASE 1 is the most 'typical' conditions, with MHWN plus the median wind speed. CASE2-7 use the same water level, HAT (likely to be exceeded every few years due to storm surge (Pugh, 2004) with a range of wind speeds. CASE6 represents the maximum wind speed observed during 2004-5 but with quite a high water level. Higher winds speeds are used in CASE7 and CASE8 although we do not have the actual return period of such wind events, CASE8 is a 'worst-case-scenario' based on the estimate of the 1 in 100 year water level from Dixon and Tawn (1995) and a severe wind case. Note that this does not correspond to the maximum possible surge case above HAT, surges at Liverpool can be 1-2m. No account is taken of the joint probability of waves and water level. CASE9 is intended to represent this case with a climate change scenario of sea level rise of 25cm and an intensification of wind-speed of 10%. No attempt is made here to estimate the probabilities of such an event.

	Water level (m)	Wind speed (m/s)	Boundary wave height (m)	Boundary peak wave period (s)
TIDE1	MHWS (+3.86)	20	6	10
TIDE2	MLWS (-3.72)	20	6	10
CASE1	MHWN (+2.2)	8	2.3	7
CASE2	HAT (+5.3)	8	2.3	7
CASE3	HAT	15	5	10
CASE4	HAT	17	6	10
CASE5	HAT	20	6	10
CASE6	HAT	22	6	10
CASE7	HAT	25	8	13
CASE8	1:100y (+5.9)	30	9	13
CASE9	SLR +0.25 (+6.2)	33	10	14

Table 4: SWAN runs

Results

An example of wave height and peak period for the TIDE1 and TIDE2 cases are shown in Figure 13 (a) and (b) show high water and low water respectively. Wave setup and the energy dissipation due to bottom friction are shown in Figure 14. These figures present a qualitative view of the impacts of waves. The difference from HW to LW may be seen in drastically reducing the inundated area of the estuaries, especially the Ribble, whereas the Mersey and Dee do retain substantial deep-water channels. The distinction between the areas influenced by the open boundary condition and the local wind-generated waves in shown clearly by the plots of peak wave period, in which there is a sharp change from long (10s) to shorter period (4s) waves.

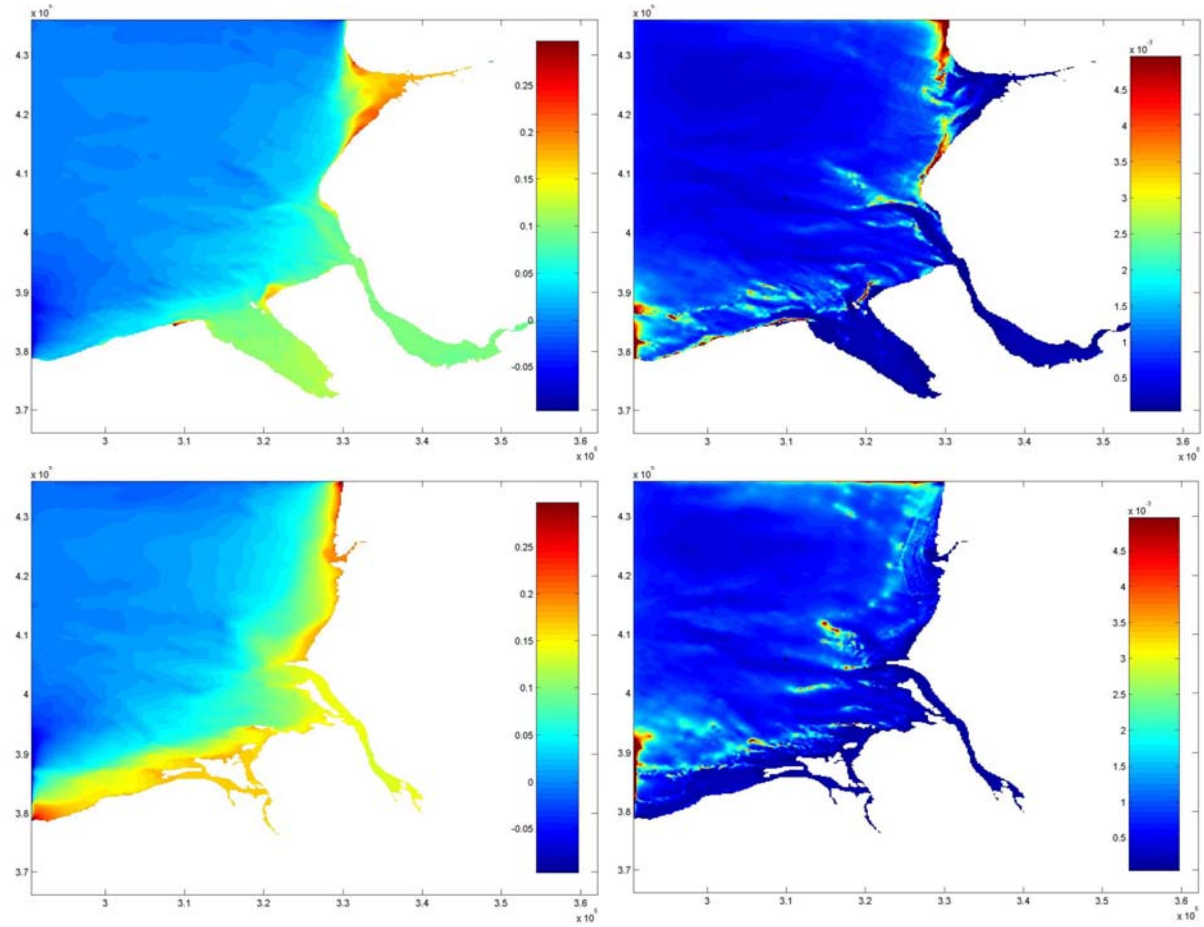


(a) (b

Figure 13: (a) Wave height (m) (b) Peak wave period (s)
Upper panel: MHWS, lower panel MLWS

At LW the wave setup occurs along the open coast and the low water channels in the Dee and Mersey estuaries, whereas at HW the setup is focussed on the specific areas like North Wirral, Point of Ayr and Formby Point. It is interesting to note that the maximum setup does occur in those areas highlighted in the flood risk maps of Figures 9 and 10. The Ribble is particularly affected by wave setup with an increase in water level up to 30cm although the wave height in the estuary only reaches 1m compared to the offshore wave height of 6m and 4.85m at the WaveNet buoy.

The areas subject to high wave energy dissipation by wave bed stress may be regarded as particularly susceptible to erosion. These areas are just offshore of the coast at LW but move towards the estuary mouth at HW, impacting on the ebb and flood shoals and especially the sand bars at the mouth of the Ribble.



(a) (b)

Figure 14: (a) Setup (m) for 20m/s NW wind (b) Dissipation due to bottom friction (m^2/s)
Upper panel: MHWS, lower panel MLWS

The point output is summarised in table 5, with the output at a subset of locations in the order of the case studies in table 4, from CASE1-CASE9. The water depth at each station is the combination of the bathymetric depth plus the still water level specified (assumed to be composed of tide plus surge), plus the wave setup generated within the model. Note that for CASE1 the water level was too low to have a wet point at several locations. This case may perhaps be regarded as the benchmark for the present-day equilibrium situation as it represents the most frequently-occurring water level and the median wind-speed. In some sense the present-day morphology is in a dynamic equilibrium and extreme events may disturb this balance.

	Depth(m)	Ws(m/s)	Hsig(m)	Tm01(s)	Tm02(s)	Tpeak(s)	Dir(deg)	Dp(deg)	Setup(m)
Point of Ayr	0.60	8	0.35	4.99	4.12	7.2	347	355	0.02
	3.53	8	0.95	5.36	4.54	7.24	341	345	0.00
	3.57	15	1.70	7.48	6.33	10.47	344	345	0.04
	3.60	17	1.82	7.92	6.55	11.49	344	345	0.08
	3.60	20	1.80	7.05	5.88	10.47	343	345	0.07
	3.60	22	1.81	6.77	5.63	10.47	342	345	0.08
	3.70	25	1.92	7.03	5.57	12.60	343	345	0.17
	4.32	30	2.18	6.24	5.08	12.60	339	345	0.19
	4.67	33	2.33	6.00	4.94	13.82	336	345	0.24
Hilbre Island	13.83	8	0.75	3.68	3.03	7.24	308	325	0.01
	16.77	8	1.07	4.79	4.04	7.24	304	315	0.01
	16.82	15	1.87	5.45	4.50	9.55	304	315	0.05
	16.85	17	2.03	5.52	4.52	10.47	306	315	0.08
	16.84	20	2.22	5.25	4.44	9.55	305	315	0.07
	16.84	22	2.35	5.10	4.38	9.55	305	315	0.07
	16.93	25	2.57	4.98	4.29	12.60	303	315	0.16
	17.56	30	3.13	5.13	4.58	5.48	300	315	0.19
	17.90	33	3.41	5.22	4.72	6.01	299	315	0.23
Flint	1.99	8	0.18	1.52	1.38	2.18	317	315	0.02
	4.93	8	0.28	2.01	1.80	2.62	325	325	0.01
	4.99	15	0.54	2.35	2.09	3.15	322	315	0.07
	5.03	17	0.62	2.42	2.15	3.45	322	315	0.11
	5.02	20	0.73	2.50	2.23	3.45	320	315	0.10
	5.03	22	0.82	2.57	2.30	3.79	320	315	0.11
	5.12	25	0.99	2.74	2.45	3.79	319	315	0.20
	5.75	30	1.28	3.09	2.74	4.56	319	315	0.23
	6.10	33	1.44	3.26	2.89	4.56	319	315	0.27
Neston	-	-	-	-	-	-	-	-	-
	1.35	8	0.20	1.50	1.37	1.98	278	285	0.01
	1.42	15	0.33	1.62	1.48	2.18	278	265	0.07
	1.45	17	0.38	1.67	1.52	2.18	278	265	0.11
	1.45	20	0.45	1.76	1.61	2.39	277	265	0.11
	1.45	22	0.50	1.84	1.67	2.39	276	265	0.11
	1.55	25	0.58	1.98	1.79	2.62	274	265	0.21
	2.18	30	0.87	2.46	2.21	3.45	273	275	0.24
	2.53	33	1.01	2.68	2.40	3.79	272	275	0.28
Ellesmere Port	1.12	8	0.13	1.38	1.23	2.39	338	345	0.01
	4.07	8	0.28	1.86	1.70	2.39	318	325	0.01
	4.12	15	0.58	2.37	2.15	3.45	322	325	0.06
	4.15	17	0.67	2.49	2.25	3.45	323	325	0.09
	4.14	20	0.80	2.64	2.39	3.79	323	335	0.08
	4.14	22	0.91	2.77	2.51	4.16	324	335	0.08
	4.24	25	1.08	2.94	2.67	4.56	324	335	0.18
	4.86	30	1.37	3.28	2.98	5.00	323	335	0.20
	5.21	33	1.53	3.46	3.14	5.48	323	335	0.24
Formby Point	0.12	8	0.18	5.47	4.79	7.24	284	285	0.05
	3.02	8	1.26	5.95	5.40	7.24	285	285	0.00
	3.08	15	1.79	7.71	6.82	10.47	285	285	0.07
	3.12	17	1.86	8.00	6.92	11.49	285	285	0.11
	3.12	20	1.83	7.21	6.26	10.47	284	285	0.10
	3.13	22	1.83	6.96	5.99	10.47	283	285	0.11
	3.23	25	1.91	7.26	5.91	12.60	281	295	0.21
	3.85	30	2.21	6.52	5.42	12.60	277	265	0.23
	4.19	33	2.42	6.37	5.33	13.82	274	265	0.27

Southport	-	-	-	-	-	-	-	-	-
	3.02	8	1.26	5.95	5.40	7.24	285	285	0.00
	1.94	15	0.74	4.40	3.17	9.55	303	305	0.15
	1.99	17	0.78	4.24	3.04	11.49	300	305	0.20
	1.98	20	0.78	3.59	2.72	9.55	298	305	0.19
	1.98	22	0.79	3.38	2.60	9.55	296	275	0.19
	2.10	25	0.85	3.43	2.60	12.60	294	275	0.31
	2.72	30	1.12	3.75	2.90	12.60	286	265	0.33
	3.06	33	1.28	3.95	3.08	13.82	283	265	0.37
Lytham St. Anne's	-	-	-	-	-	-	-	-	-
	1.71	8	0.45	4.06	3.01	7.24	252	255	0.03
	1.81	15	0.63	4.23	3.03	10.47	250	255	0.13
	1.86	17	0.66	4.22	3.02	11.49	250	255	0.18
	1.85	20	0.66	3.62	2.72	9.55	251	255	0.17
	1.85	22	0.67	3.43	2.61	9.55	252	255	0.17
	1.97	25	0.74	3.55	2.67	12.60	252	255	0.29
	2.60	30	1.01	4.01	3.06	12.60	253	255	0.32
	2.95	33	1.17	4.29	3.29	13.82	253	255	0.38

Table 5: Summary of case studies

DISCUSSION

In general there is a monotonic increase of wave height, period and setup with increasing wind-speed and water depth. In very shallow water when the wave height reaches half the water depth or more, depth-limited breaking is initiated which can cause a local reversal of the trend. The largest wave setup is predicted at Lytham St. Anne’s and Southport at the mouth of the Ribble, reaching over 30cm in the present-day worst-case scenario and increasing by another 5cm in the future climate scenario. This could contribute significantly to flooding, although no data on surge levels at these locations were obtained, it is assumed a surge can be of the order of 1m as at Liverpool.

The results presented here are an illustration of the possible effects of waves in the Dee, Mersey and Ribble estuaries. They consist of a set of case studies, devised based on a limited amount of existing wind and wave data, using the SWAN model to provide detailed spatial information on the variation of wave parameters, effects of wave bed stress and wave setup. The probability of the extreme events shown here cannot be determined without further work.

Further improvements could be made in the wave model. For example, SWAN could be used in non-stationary mode on an unstructured grid. Both of these options are now available. To avoid parametric boundary conditions the model could be nested within a coarser grid Irish Sea model. Further work could be done to investigate the optimum source terms. Using output from the POLCOMS tidal model would provide accurate and time- and space-varying water levels and currents. The wind and wave climate can be determined more precisely when longer time series of wind and wave data become available.

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