



Malta Significant Wave Height Study

Main Report

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1. Background

1.1 Overview

The Maltese Islands are located in the central Mediterranean Sea: 93km south of Sicily and 290km from the north coast of Africa. The archipelago consists of the Islands of Malta, Gozo and Comino, together with two other uninhabited islands (Figure 1.1).

There are no bridges or other fixed links between the islands. Therefore, inter-island maritime connections for the transportation of passengers and cargoes are of utmost importance, particularly for the economic development of the smaller islands. Moreover, tourism is the main economic activity in Malta and there are many vessels providing passenger cruises around the islands.

The Malta Maritime Authority promulgated new legislation in 2002 to regulate boats, operating exclusively within local territorial waters and ports. The previous regulations dated back to 1955, and were not in line with EU standards. The new regulations are intended to ensure a harmonised regime for all operators and to set minimum safety and pollution prevention standards. They are complemented by a Code of Practice for the construction, machinery, equipment, stability, manning and maintenance of vessels in local commercial use. This includes vessels operated for the carriage of cargo and passengers and vessels employed in port services and the servicing of ships.

At present there are about 200 vessels operating exclusively within territorial waters. They range from small traditionally built boats capable of carrying only 8 passengers to the large RORO ferries, capable of carrying 800 passengers and up to 146 vehicles, employed in scheduled ferry services between the Maltese islands.

EU Directive 98/18/EC of 17 March 1998 establishes safety rules and standards for passenger ships in order to ensure a uniform level of safety of life and property. The extent of applicability depends on the characteristics of the sea area in which the passenger vessel operates. The Directive establishes four classes of passenger ships. The sea area depends on the distance from the shore and the wave heights within the area. This data is not available to the Authority and therefore it is not in a position to classify ships as required by the Directive. It is for this purpose that this study was commissioned.

1.2 Linked Activities

This study is part of the Maritime Safety Project Fiche which also involves a Twinning project, which is lead by France. This project provides the basis for institution building of the administrative capacity, advice on the establishment of a dangerous goods notification procedure, requirements for the operation of Vessel Traffic Management System and the drawing up of a Port Waste Management Plan.

The Ports Directorate is also actively participating in the EUMEDIS and the MEDCHART projects financed by the MEDA Fund. The objective of these projects is to upgrade the Mediterranean Hydrographic Offices of the Mediterranean countries by providing the necessary technical equipment, software and training. The main result would be that each country would be in a better position to carry out maritime

hydrographic surveys around their coasts and produce their navigational charts. This would also help the Directorate to continue monitoring wave heights around Malta.

2. Terms of Reference and Methodology

2.1 Terms of Reference

The Terms of Reference for the Study were set out in an attachment to Framework Contract AMS/451 Lot No. 2, Request for Services No. 2003/63200 Version 1.

The purpose of the Study is to enable the Government of Malta to comply with EU Directive 98/18/EC of 17 March 1998. The EU Directive establishes safety rules and standards for passenger ships in order to ensure a uniform level of safety of life and property. The extent of applicability depends on the characteristics of the sea area in which the passenger vessel operates. The sea area classification depends on the distance from the shore and the wave heights within the sea area.

The objectives were listed in the Terms of Reference (ToR) as:

1. Provide information on significant wave heights (SWH) for the sea area up to 20 nautical miles around the Maltese Islands;
2. Determine the local sea areas where the probability of exceeding 2.5m SWH is smaller than 10% over a one-year period for all-year-round operation and for summer period operation (April to October inclusive);
3. Determine the sea areas where the probability of exceeding 1.5m SWH is smaller than 10% over a one-year-period for all-year-round operation and for summer period operation (April to October inclusive).

2.2 Methodology

The following is a summary of the methodology that has been employed in the study. The methodology followed has in part been developed with the MMA during the project team's visit to Malta.

Collection of Datasets and Reports

Available datasets were obtained, including: existing studies, wave model results, wave measurements, wind measurements, water level and bathymetry information.

During the early stages of the project, the team spent a period in Malta. During this time in-country, relevant data sources were identified, both on a local and regional basis. A series of meetings were held with organisations that were likely to hold relevant information. Section 3 gives a summary of these meetings and the details of the data collection exercise.

Review of Datasets

The extent and quality of data sets obtained was reviewed and is presented in Section 4. The collection techniques for each dataset obtained were assessed to determine whether the resulting information is consistent.

The geographical coverage of the datasets has been assessed, as has the period for which data is available. Gaps in the datasets have been identified and the implications of this in the usage of the information assessed.

The final part of Section 4 details which datasets have been selected for use in the preparation of statistical information and the determination of significant wave height sea areas.

Data Analysis

The selected data sets have been analysed and presented in the form required by the Terms of Reference. This includes the generation of statistical tables and rose plots for wind and waves in the Maltese area (see Section 5).

A comparison has been made between wind and wave data obtained from different sources.

Significant Wave Height Sea Areas

In order to generate the significant wave height sea areas, a numerical modelling exercise has been undertaken. Section 6 gives details of the methodology employed and the results obtained.

The MIKEZero suite of numerical wave models, developed by the Danish Hydraulic Institute, have been used to determine wave conditions in the sea areas around Malta. This modelling software is state-of-the-art and has been used extensively on projects around the world.

The numerical models cover an area which is approximately 100km by 100km and is sufficient to derive results for the area of interest i.e. results up to 20 nautical miles from the coastline.

The wave models use a digital representation of the seabed enabling complex sea areas to be represented (e.g. islands, channels). The digital ground models used in the models have been derived from available Admiralty Charts of the area.

Initially the offshore wave/wind climate has been derived (Section 5) and this has been used as the basis for numerical modelling. The wave climate around the islands has then been derived through model simulations, which represent all of the conditions that occur annually around Malta.

The models results have been compared with available datasets to verify the output of the model.

The results from the model simulations have then been analysed to determine the sea areas where the probability of exceeding significant wave heights of 1.5 and 2.5 m is less than 10%. The modelling exercise has been completed on an annual basis and for a summer period (April to October inclusive).

2.3 Deliverables

The deliverables for the study are as follows:

1. Statistical tables on wind speed and wave heights up to 20 nautical miles around Malta. Separate tables have been prepared for annual and seasonal results. Wave and wind roses have also been prepared to graphically show annual and seasonal statistical information.
2. A report on the quality of the available datasets, the assimilation procedure and the results of the analysis e.g. statistical comparisons.
3. Contour maps of SWH for the Maltese Islands to 20 nautical miles offshore of the coastline. Contoured 10 percentile values of SWH have been determined at 0.5m intervals from 1.5m and above. Two maps have been produced: annual climate and summer climate (April to October).
4. A report detailing the methodology, datasets obtained, techniques used (e.g. numerical modelling) and the results of the analysis. The report includes maps in hardcopy and these have been included in electronic format on a CD-ROM.

This report contains all of the above deliverables.

3. Collection of Background Information, Datasets and Reports

3.1 In-country Meetings

The data collection exercise included a series of meetings during the team's visit to Malta.

Malta Maritime Authority (MMA)

The Institute for Insular Coastal Dynamics (IcoD), Malta University Oceanography Dept., Malta Met. Office and CMC (consulting arm of the Freeport) were discussed as possible suppliers of data. Scott Wilson (SW) suggested the UK Met. Office as the supplier of wave data.

Meetings were had with a number of MMA officers including Charles Abela, Joe Bianco, David Bugeja, Chris Farrugia and Alfred Xeureb. Alfred Xeureb provided many useful reports.

Institute for Insular Coastal Dynamics (ICoD)

The Euro-Mediterranean Institute for Insular Coastal Dynamics (ICoD) is undertaking a research project to develop a 40-year time series of historical wave data in the Eastern Mediterranean on a 16 km grid. Their model uses wind speeds from a global wind model and uses these to forecast wave conditions according to the WAM (Wide Area Model) approach. The model has been validated against specific events, but is not routinely validated using measured data.

ICoD expect that their results will be available in several months. ICoD do not currently hold data suitable for the study.

Malta International Airport (MIA) Meteorological Office

MIA was able to provide statistics in the form of mean hourly wind speeds for the 20-year period 1972-1991, measured at Luqa Airport. Through MMA, MIA provided detailed wind information for 2000-2002, and had similar data available for 1999 and 2003.

MIA data is also available for other sites in Malta, but these sites have shorter and less reliable data sets (less than 5 years data).

MIA receives wind (and other climatological data) forecasts from three sources on a routine basis: UKMO, INM (Spanish Met. Office) and European Medium Range Forecasting Centre. The MIA forecasters use all three sources to compile a forecast. Generally the three sources show similar data, but may differ when winds are very light.

MIA does not retain any wave data. MIA confirmed that they obtain wave height forecasts from UKMO's European Wave Model on a twice-daily basis and use this data for their sea state forecasts (MMA advised subsequently that these forecasts are of reasonable accuracy). The Chief Meteorological Officer at MIA is of the

opinion that the UKMO wave data is of acceptable accuracy for the seas around Malta.

Coastal Management Company (CMC)

The Coastal Management Company (CMC) has offshore data for Hurd Bank from 1992 to 2000. This is from a waverider buoy, and is in form of 1- and 3-hourly records. There are only a limited number of downtime periods within this.

Scott Wilson made a formal inquiry regarding this data on 10 July 03 but received no reply. Statistics from the data were provided by MMA.

3.2 Reports

The MMA made the following reports available to SW, these are discussed in Section 4:

Coode Blizard Ltd. (1990) Malta, Marsamxett Harbour M'Sida Wave Study, Report. April 1990.

Coode Blizard Ltd. (1991) Malta, Grand Harbour Rinella Creek Developments, Wave Study, Report. January 1991.

Cottonera Waterfront Group (2000) Wave Disturbance Modelling of Dockyard Creek, Progress Report May 2000.

Gozo Ferries Co. Ltd. (1998) Vertical Ship Motions in Harbour Conditions. Report DMC 40.2187.03. May 1998.

HR Wallingford (1993a) Wave Prediction Study at St Paul's Bay, Malta. Report EX2873. September 1993.

HR Wallingford (1993b) Wave Prediction Study at Marsascala Bay, Malta. Report EX2897. October 1993.

HR Wallingford (1996) North Cirkewwa Ferry Terminal, Malta, Wave Modelling Studies. Report EX3408. April 1996

Svasek (1998) Mathematical Wave Study for Cirkewwa Ferry Terminal, Malta. February 1988.

Svasek (1999). SWAN Wave Computations, Cirkewwa, Malta. June 1999.

UK Met Office (1998) Assessment of Significant Wave Height in UK Coastal Waters, UK Met Office Marine Consultancy Service. Report No. M/CI/BGM/16/5/1/6. August 1998.

3.3 Wave Data

UK Meteorological Office (UKMO)

The UKMO advised that their European Model provides forecasts every 3-hours on a grid spacing of approximately 35 km (depending on latitude). A plot of the model grid is shown in Figure 3.1. Due to the grid spacing and model set-up, the Maltese islands are not represented in the model. The wave model archive consists of the hindcast fields of winds and waves produced during the operation of the atmospheric and wave model forecast. Available reports of surface pressure, wind speed and direction (from ships, buoys, platforms, ERS-1 and DMSP satellites and land stations) are subjected to a range of consistency checks before being assimilated into the model's analysis.

The resulting wind field is then applied to modify the wave field derived at the previous time-step, using 16 directional and 13 frequency bands. Wave height is calculated at each model grid point, using the wind field and taking into account propagation, dissipation and transfer of energy between spectral bands.

The UKMO wave data set contains both swell and locally generated waves. The height is the combined height for both components, but the period presented is the period for the highest component. Normally this is the locally generated component.

The model is run continuously in real-time, and the resulting wave conditions are archived every 3 hours. The model operates on a 35km grid, with depth dependency. The model has been operational since 1988, so there is now a 14 year validated 3-hourly data set for the seas around Malta.

A detailed description of the UKMO European Wave Model is given in Appendix 1.

ECMWF Archives

The European Centre for Medium-Range Weather Forecasts (ECMWF), based in the UK, has been archiving results from its operational wave models since 1992. The commercially available database consists of archived results from the ECMWF Wide Area Model (WAM) on a 0.5° Lat/Long grid every 6 hours. The model has been subject to extensive calibration/validation with measured datasets e.g. satellite data.

World Wave Atlas

The World Wave Atlas (WWA) is a commercially available database of wave information supplied by the Norwegian company OCEANOR. The wave atlases contain wave data from the following sources:

- Remote sensed GEOSAT data (1986-89)
- Remote sensed Topex/Poseidon (1992-ongoing)
- Available wave buoy data e.g. US national Oceanographic and Atmospheric Administration (NOAA)
- Quality controlled wave data from a global wave model (UK Meteorological Office)

4. Review of Datasets and Reports

4.1 A review of available reports

MMA hold a number of reports undertaken for previous projects. In report date order, a brief synopsis of each is as follows.

Coode Blizard Ltd. (1990) Malta, Marsamxett Harbour M'Sida Wave Study, Report. April 1990.

Offshore wave conditions were determined by HR Wallingford for a point close to the 100m chart datum contour, adjacent to Valletta. Offshore conditions were derived from analysis of Voluntary Observed Ship (VOS) data. Only extreme heights were reported, rather than statistics of the climate. The maximum 1 in 1 year wave height is 4.6m H_s from 016° -045° sector.

The report also contains wind data from Luqa Airport (in the form of 1 in 1 year, 1 in 10 year etc. extreme wind speeds) for 1-hour mean duration records between 1958-1987.

Coode Blizard Ltd. (1991) Malta, Grand Harbour Rinella Creek Developments, Wave Study, Report. January 1991.

The offshore wave climate was taken from 1990 Coode Blizard report (above). These conditions were transformed inshore to a point on the -20m contour using OUTRAY wave model. The 1 in 1 year significant wave height is 4.0m.

HR Wallingford (1993a) 'Wave Prediction Study at St Paul's Bay, Malta. Report EX2873, September 1993.

Report prepared for MMA by HR Wallingford to investigate the suitability of St Paul's Bay as a location for a yacht marina development.

A wave refraction model was used to transform offshore extreme waves to nearshore locations in St Paul's Bay. The offshore extremes were calculated from VOS data for the area 35.5°N to 36.5°N and 14°E to 15°E. The VOS data was based on over 10,000 observations recorded in the area between the period 1/1949 to 9/1992. Approximately 50% of the recorded observations were in the direction sector between west and north. The 10%ile exceedance significant wave height was in the wave height band of 2.1 to 2.5m.

HR Wallingford (1993b) 'Wave Prediction Study at Marsascala Bay, Malta. Report EX2897, October 1993.

Report prepared for MMA by HR Wallingford to investigate the suitability of Marsascala Bay as a location for a yacht marina development.

A wave refraction model was used to transform offshore extreme waves to a location at the entrance to the bay. The wave conditions inside the bay were predicted using a wave refraction-diffraction model. The offshore extremes were calculated from VOS data for the area 35.5°N to 36.5°N and 14.5°E to 15.5°E. The VOS data was based on over 17,000 observations recorded in the area between the period 1/1949

to 9/1988. The data showed that nearly 50% of the recorded observations were in the direction sector between west and north. The 10%ile exceedance significant wave height was in the wave height band of 2.1 to 2.5m.

The inshore wave conditions for a return period of 1 year at the entrance to the bay corresponding to offshore wave direction of 90° and significant wave height of 4.2m (and wave period of 8.2s) were a direction of 97° and significant wave height of 1.9m.

Coastal Management Company Ltd (1995) Wave Data Statistics from Offshore Wave Monitoring Buoy 1992-1994. Report GC 9502 prepared for Gozo Channel Co. Ltd. May 1995.

The report presents statistics from a wave buoy was deployed at 35° 49' 00" N, 14° 43' 30" E, approximately 10 km to the east of Malta on the Hurd Bank in approximately 45m of water. The data covers the period October 1992 to August 1994. Hourly/3-hourly observations were processed to 1 hourly equivalent. There are a total of 10263 observations.

Data presented in tabular statistical form, showing monthly frequency of occurrence by height, direction by height, period by height for direction sectors. It is not clear why the number of observations reported in some months differs so markedly from the number which would be expected for this duration of deployment. In a meeting CMC advised that the most likely reason was a loss of data due to buoy not functioning or being off station.

HR Wallingford (1996) North Cirkewwa Ferry Terminal, Malta, Wave Modelling Studies. Report EX3408. April 1996

Report prepared for MMA by HR Wallingford to support design of harbour layout for ferry to Gozo. This report contains statistics of offshore climate in form of VOS data for large sea area around Malta. Also results of wave modelling to transfer 0.1, 1, 10 and 100 year events to locations at Cirkewwa.

Svasek (1998) Mathematical Wave Study for Cirkewwa Ferry Terminal, Malta. February 1988.

Report prepared for MMA. See comments for the HR Wallingford report (1996) above.

Gozo Ferries Co. Ltd. (1998) Vertical Ship Motions in Harbour Conditions. Report DMC 40.2187.03. May 1998.

The objective of the report was to determine ship motions for a double-ended ferry exposed to waves within the revised Cirkewwa harbour. The wave spectrum for Cirkewwa berth no. 2 was provided by the Rotterdam based company, Svasek.

UK Met Office (1998) Assessment of Significant Wave Height in UK Coastal Waters, UK Met Office Marine Consultancy Service, August 1998 report no. M/CI/BGM/16/5/1/6.

In 1998 the UK Maritime and Coastguard Agency (MCA) undertook a study for the coasts of the UK with the same objectives as the current study – to meet the requirements of EU Directive 98/18/EC. The UK Meteorological Office (UKMO) was commissioned to provide maps of significant wave height contours.

The UKMO did not undertake any specific numerical wave modelling for the study. Their methodology had the following main elements:

- Data was extracted from Voluntary Observations from Ships (VOS) data and from the UKMO European Waters Wave Model, which has a grid point resolution of 25 km;
- At each grid point the data was analysed to determine the 10%ile exceedance value
- The 10%ile exceedance values were plotted on maps and contours drawn at 0.5m intervals from 1.5m to 4m.
- In the sheltered channels of the Western Isles, the results were supplemented by a simple wind-wave hindcasting method

Some key aspects of the approach were:

- Results were not specifically validated, as the UKMO wave model archive had already been validated
- Sensitivity tests showed that a significant improvement in accuracy would be obtained by using a data set of 10 years or more compared to a data set of 2 or 3 years.
- Contours were drawn smoothly and to a scale ranging from about 1 in 200,000 to about 1 in 3,000,000.
- Contours were drawn at 0.5m intervals from 1.5m to 3.0m and then 1.0m intervals.

Svasek (1999). SWAN Wave Computations, Cirkewwa, Malta. June 1999.

Report prepared for MMA by Svasek to support the design of harbour layout for ferry to Gozo. The report presents a 0.1 year return period significant wave height of 2.6m for point just seaward of north Cirkewwa terminal in 19 m of water, which compares to a SWH of 2.7m offshore 0.1 yr return period from VOS data, for direction sector 260°-270° deg.

The 1 in 1 year return period SWH is 4.6m offshore and 4.3m inshore.

Wave model results are also given for a location in 27m water depth which is about 3 km east into channel and 2 km to north. At this location the offshore 0.1 year return period significant wave height is 2.4m for 090° inshore and 1.3m offshore. The 1 in 1 yr height inshore significant wave height is 2.0m.

RP1 is 1 km east of west point in 13m of water, significant wave height for 1 in 1 year is 0.7 compared to 1.1m found by HR Wallingford.

Cottonera Waterfront Group (2000) Wave Disturbance Modelling of Dockyard Creek, Progress Report May 2000.

This report includes a numerical modelling report by HR Wallingford. Offshore conditions were taken from the Coode Blizard report 1990. The report contains wind frequency data in table form for Luqa airport, January 1984-December 1993. Data is in the form of hourly mean wind speeds by 3ms^{-1} bands and direction sectors.

4.2 Summary

After a review of the available information, the following datasets were selected for use in the assessment:

Offshore wave conditions: UKMO European Wave Model

There are various possible sources of offshore wave data. The UKMO model is used by the MIA Met. Office as the basis for their sea state forecasts. It provides adequate coverage for the seas around Malta and has an adequate length of record to derive the statistics of significant wave height. The data set was also the basis for an analogous study of wave climate for UK waters (UK Met Office, 1998). It is considered that data archives from this model provide an acceptable approach to defining the offshore conditions.

Offshore wind conditions: MIA Met Office & UKMO Global Wave Model

The UKMO European Wave Model archives include wind speed. For the reasons given above it is considered that this is an acceptable source of offshore wind data. The data has been compared with MIA Met Office records (Section 5).

Model setup - sea bed level data (bathymetry): Admiralty Charts

The UK Admiralty Charts provide adequate sea bed level data, which was used to create a high quality digital ground model for the wave modelling.

Model verification - offshore wave conditions: CMC (1995)

The offshore wave statistics derived from the modelling approach have been validated against the 2 years off wave data recorded at Hurd Bank by CMC (CMC, 1995).

Model verification – nearshore wave conditions: HR Wallingford (1996), Svasek (1999) & Coode Blizard Ltd. (1991)

Conditions closer inshore, particularly in the channels, will be strongly affected by local bathymetry and presence of land masses. To determine accurately conditions in these waters requires either a measurement campaign or the use of a wave refraction model. No inshore wave measurements have been made for the sea area around Malta, therefore inshore conditions have been validated against the most relevant modelling reports identified (*HR Wallingford, 1996; Svasek, 1999; Coode Blizard Ltd., 1991*). These have allowed validation of specific conditions at Cirkewwa and Valletta.

5. Data Analysis

5.1 Offshore Wind Conditions

Wind data from the UKMO European Wave Model was obtained for 2 points (Figure 5.1):

Point B	14.7°E, 36°N	East of Malta
Point D	13.9°E, 36°N	West of Malta

These data sets were in the form of statistics based on the 14 year period of archived model results. The UKMO data has been compared with the MIA wind dataset measured over the 20-year period between 1972 and 1991.

Statistics for the offshore UKMO wind data and MIA data are given in Tables 5.1 and 5.2, for the annual and summer periods of operation respectively. A comparison between the three locations for which wind data has been obtained is given in Figures 5.2 and 5.3. These plots demonstrate that the wind statistics for the offshore location Points B and D (east and west of Malta respectively) are very similar. The offshore wind data from the model archive compares well with the data from the MIA. As would be expected, the wind conditions are slightly milder than offshore, due to the sheltering effects of the landmass. When Figures 5.2 and 5.3 are compared it can be seen that the wind speeds are less in the summer period of operation than for the whole year. The wind speed that is exceeded for less than 10% of the time is around 9.5m/s annually and 9.0m/s for the summer period of operation.

Figure 5.4 shows a wind rose for Point D and demonstrates that the area is dominated by winds from the north-west. As the data for Point B is very similar it has not been plotted. A wind rose for the summer period of operation for Point D is shown in Figure 5.5. When Figures 5.4 and 5.5 are compared it can be seen that the directional distribution of wind is similar for the annual and summer periods of operation.

Figures 5.6 and 5.7 show wind roses derived from the MIA data for the annual and summer periods of operation respectively. As would be expected, these wind roses also show a dominance of north-westerly winds for both periods of operation.

5.2 Offshore Wave Conditions

UKMO European Wave Model Data

Wave data from the UKMO European Wave Model was obtained for 4 offshore locations (Figure 5.1):

Point A	14.3°E, 35.75°N	North of Malta
Point B	14.7°E, 36°N	East of Malta
Point C	14.3°E, 36.25°N	South of Malta
Point D	13.9°E, 36°N	West of Malta

These data sets were in the form of statistics based on the 14 year period of archived model results between 1988 and 2002. Statistics for the offshore UKMO wave data

are given in Tables 5.3 and 5.4, for the annual and summer periods of operation respectively.

A comparison between the wave data from points A, B, C and D is given in Figure 5.8 and 5.9 for the annual and summer periods of operation respectively. It can be seen from the plots for both periods of operation that the significant wave height data is very similar for all the offshore locations. As would be expected the significant wave heights are milder for the summer period when compared to the annual period of operation. The offshore significant wave height that is exceeded for less than 10% of the time is around 2.1m annually and 1.75m for the summer period of operation.

Significant wave height roses for the annual and summer periods of operation are given in Figures 5.10 and 5.11 respectively. From these plots it can be seen that the predominant wave direction is from the north-west. Waves from the south-east are also relatively frequent but waves with directions from the south-east and north-east occur less frequently.

The offshore wave roses (Figures 5.10 and 5.11) have a very similar directional distribution to the offshore wind roses (Figures 5.4 and 5.5). This confirms that the wave climate around Malta is dominated by sea waves rather than swell waves. Sea waves are characterised by being steep and having relatively short wave periods when compared to swell. Sea waves are generated by the wind in the local area, whilst swell waves are waves that have been generated elsewhere and have travelled into the local area.

Figure 5.12 shows the distribution of significant wave heights by height band for each of the months between March and November for Point D. Point D is similar on a month-to-month basis to the other three points therefore only one is shown. These plots have been produced to demonstrate how the wave conditions change during the summer period of operation. The % occurrence for each month has been taken over the period 1988-2002 and, for example, 20% translates as roughly 6 days of each month. The plot shows that August is the mildest month in terms of wave climate with over 60% of wave heights being in the lowest wave height band of 0-0.5 (indicated as 0.25 on the plot). The wave height distribution for June and July is similar to that of August.

Figure 5.12 demonstrates that the wave conditions in May are similar to those in September. In general the wave conditions are slowly varying throughout the year, which means that results for the summer period of operation would not be significantly affected by small changes in the start or end dates of the summer period.

CMC Wave Buoy Data

The Coastal Management Company (CMC) recorded wave conditions in the vicinity of Hurd Bank between 1992-1994 (CMC, 1995). Significant wave height exceedance statistics from this dataset are plotted in Figures 5.13 and 5.14 for the annual and summer periods of operation respectively. The significant wave height that is exceeded for less than 10% of the time is approximately 2.4m annually and 1.9m for the summer period of operation. This compares well to both the UKMO wave model dataset (above) and the VOS datasets reported in HR Wallingford (1993a & b).

Figures 5.13 and 5.14 compare the CMC data with the UKMO model for the offshore Point B, which is located in the vicinity of Hurd Bank. The plot demonstrates that the

two wave data sets, recorded by the CMC buoy and extracted from the UKMO model, are comparable. For a given wave height, the UKMO wave model data occurs less frequently than the CMC data, demonstrating that the UKMO dataset is milder in terms of wave climate. However the difference between the two wave climates is small and may be due to the difference in record length of the datasets i.e. 2 years for the Hurd Bank data and 14 years for the UKMO model data. Differences of this magnitude between recorded and modelled data at site-specific locations are normal. A description of the comparison of between the UKMO European Wave Model and a wave buoy is given in Appendix 2.

In conclusion, the similarity of the CMC and UKMO wave datasets supports the selected approach (see Section 4.2) of using the UKMO wave model as the base dataset for the numerical modelling which has been used to determine detailed wave conditions in sea areas close to Malta (Section 6).

6. Significant Wave Height Sea Areas

6.1 Methodology

As the Maltese Islands are not represented in the UKMO European Wave Model, a detailed numerical model has been developed for the area around Malta and Gozo using the Mike Zero Nearshore Spectral Wave (NSW) model, a nearshore modelling package developed by Danish Hydraulic Institute (DHI).

The model has been constructed using a digital ground model of the seabed around Malta, digitised from Admiralty Charts.

The model has been applied to simulate all the wave conditions in the 14 year UKMO wave model dataset. The results from these simulations have been extracted across the nearshore area. This dataset has been analysed to determine the 10%ile exceedance significant wave height values. These values have been plotted and contoured according to the requirements of the Terms of Reference (Section 2).

The model has been run for both the annual climate and summer climate, the summer climate being represented by the months April to October inclusive.

6.2 Modelling Tools

MIKE 21 NSW is a wind-wave model that describes the propagation, growth and decay of short-period and short-crested waves in nearshore areas. The model takes into account:

- Spectral energy distribution
- Refraction
- Weak diffraction
- Breaking
- Shoaling
- Bottom friction
- Local wind field

MIKE 21 NSW is a stationary, directionally decoupled, parametric model. The basic equations are solved using an Eulerian finite difference technique. The zeroth and the first moment of the action spectrum are calculated on a rectangular grid for a number of discrete directions. A once-through marching procedure is applied in the predominant direction of propagation.

The basic output from the model is integral wave parameters such as significant wave height, mean wave period, mean wave direction, the directional standard deviation and radiation stresses. In addition, spectral output data in form of distribution of wave energy on directions at a number of user-selected points can also be obtained.

It should be noted that the model does not include reflection. Therefore it will underestimate wave heights close to reflective structures such as breakwaters. However, the area of increased wave height will be restricted to a narrow band close to the shore and neglecting this is acceptable for the purposes of determining wave conditions across broad sea areas.

6.3 Model Setup

Bathymetry

In order to run the NSW model, a digital elevation model of the seabed was created. The elevation models were digitised from the following admiralty charts of the area:

- 2124 'Isola Di Lampedusa to Capo Passero, including Malta', scale 1:300,000
- 194 'Approaches to Malta and Ghawdex (Gozo)' scale 1:100,000
- 2537 'Ghawdex (Gozo), Kemmuna (Comino) and the northern part of Malta' scale 1:50,000
- 2538 'Malta' scale 1:50,000
- 211 'Plans in the Maltese Islands' scale 1:25,000

The model was set up for an area of 100km x 100km around Malta, using the Universal Transverse Mercator (UTM) zone 33 horizontal coordinate system, with a grid size in the direction of wave angle of 100m. This selected grid size (100m) ensures that the nearshore bathymetry is represented accurately in the numerical model.

The base bathymetry data in the form of digitised contours and spot heights from the Admiralty charts is shown in Figure 6.1. The resulting bathymetry is shown in Figure 6.2.

NSW model offshore boundary conditions

The wave conditions at the edges of the NSW model (boundary conditions) have been taken from the UKMO European Wave Model for the following four offshore locations (Figures 3.1 & 5.1):

Point A	14.3°E, 35.75°N	North of Malta
Point B	14.7°E, 36°N	East of Malta
Point C	14.3°E, 36.25°N	South of Malta
Point D	13.9°E, 36°N	West of Malta

The UKMO model stores wave information at 30° direction intervals, so the boundary inputs for the NSW model were taken from the most relevant offshore data point, as follows:

Point A	330°, 0° and 30°
Point B	60°, 90° and 120°
Point C	150°, 180°, and 210°
Point D	240°, 270°, and 300°

Further details of the model are given in Section 3.3 and Appendix 1.

6.4 Model verification

Offshore

The offshore wave conditions used as the basis for the NSW modelling have been shown to be comparable with data recorded at the Hurd Bank wave buoy by CMC during 1992-1994 (see Section 5.2) and the VOS data reported in HR Wallingford (1993a & 1993b). A comparison between the NSW model results and the wave buoy dataset is given in Section 6.5.

Nearshore

Comparisons between the NSW model and available nearshore model results from previous studies have been made at Cirkewwa and Valletta.

Table 6.1 shows the results of the NSW model for the 1 year return period for offshore conditions derived in HR Wallingford (1996). HR Wallingford used the OUTRAY model to determine the conditions at the -30mCD contour to the west of Cirkewwa. The OUTRAY model uses a ray tracing technique to determine nearshore wave conditions. Svasek (1998) also completed the same simulation using the SWAN spectral wave model.

Table 6.1 demonstrates that for offshore incident wave directions of 240-300°, the predictions of wave conditions at the nearshore location using the three methods is comparable. For example, for an offshore incident wave direction of 270° and significant wave height of 4.6m, the models predict nearshore significant wave heights of 3.1, 3.5 and 4.4m for HR Wallingford (1996), Scott Wilson NSW and Svasek (1998) respectively. The table also demonstrates that the NSW inshore wave directions are within 5 degrees of those predicted in HR Wallingford (1996).

Figures 6.3 and 6.4 show examples of the wave transformation results for Cirkewwa. Figure 6.3 shows the results of the NSW model for an offshore incident wave direction of 240° and significant wave height of 2.9m. Figure 6.4 shows the results of the NSW model for an offshore incident wave direction of 270° and significant wave height of 4.6m.

The reasons for the differences in the results arise from the following causes:

- 1) Because of the geography of Cirkewwa, located at the entrance to the channel, wave conditions will be rapidly varying in space. The gradient of wave height on a line from offshore to inside the channel will be much greater than along the coast. Therefore small differences in location, and the way the model grids are set up, lead to differences in calculated wave height.
- 2) The models used by Wallingford, Svasek and Scott Wilson are formulated in different ways and each has strengths and weaknesses. Also each model makes slightly different assumptions about the energy spectrum which can only be checked by use of measured data.

The differences are not unexpectedly large as it is commonly found that wave height calculations produced by different models will show some variation. The only way to arrive at a more definitive result is to calibrate against an inshore wave measurement

at the specific site of interest. In the case of Cirkewwa this was not available and so any result has a degree of uncertainty.

A similar comparison has been undertaken for a nearshore point at -10m just to the east of the St Elmo breakwater at the entrance to Valletta harbour, using the offshore and nearshore wave conditions given in HR Wallingford (1991). Table 6.2 shows that for offshore incident wave directions of between 60-120° the HR Wallingford OUTRAY model and SW NSW model predictions of nearshore wave height are within 0.3m of each other. Predictions of nearshore wave directions are also comparable with the model predictions being within 10° for the simulations.

Figures 6.5 and 6.6 show examples of the wave transformation results for Valletta. Figure 6.5 shows the results of the NSW model for an offshore incident wave direction of 60° and significant wave height of 4.2m. Figure 6.6 shows the results of the NSW model for an offshore incident wave direction of 120° and significant wave height of 4.0m.

It is worth noting that for the Scott Wilson study, the end product is the 10%ile wave height, which is determined from running the model for a large number of wave height, direction and period combinations. This means that the 10%ile figure is more reliable than any one individual model run.

In summary, there is reasonable agreement between the predictions made by the NSW model and previous studies.

6.5 Model Results

The NSW model was set-up to represent the entire 14 year UKMO offshore dataset. For the annual period of operation this consisted of approx 40,000 wave conditions. Many of the wave conditions in the dataset were repeated during this time, so the total amount of simulations (with different combinations of incident wave height, period and direction) completed was in the order of 300 for each period of operation. The effects of wind-wave growth behind the islands was included using an analytical method.

For each model grid point, the wave conditions were extracted from the results, giving a complete representation of the 14 year dataset for the whole model area (100km by 100km). The 10%ile wave height at each model grid point was then derived using MS Excel and then these values have been plotted in the form of smooth contours in Figures 6.7 and 6.8 for the annual and summer periods of operation respectively.

For the annual period of operation (Figure 6.7) and for the wider sea area around Malta, the significant wave height that is exceeded for 10% of the year is between 2.0 and 2.5m (represented by red on the plot). As would be expected, the results for the offshore area are consistent with the offshore data points from the UKMO European wave model and the VOS data given in HR Wallingford (1993a & b). The results are also consistent with the wave observations made by CMC at Hurd Bank (CMC, 1995).

The significant wave height that is exceeded for 10% of the year is between 1.5 and 2.0m (represented by yellow on the plot) for a sea area that extends approximately 20km offshore to the north-east of the islands and 10km to the south-west.

The sea area where the 10%ile exceedance significant wave height does not exceed 1.5m does not extent all the way around the islands (represented by blue on the plot). To the north of the islands the sea area extends out to about 5km from the coastline. There are two coastal areas where the 10%ile exceedance significant wave height exceeds 1.5m: (1) to the north-west of Gozo and (2) to the south of Malta. The main sea routes between Malta, Comino and Gozo all fall within the lowest specified significant wave height band (<1.5m).

For the summer period of operation (Figure 6.8) and for the wider sea area around Malta, the significant wave height that is exceeded for 10% of the period is between 1.5 and 2.0m (represented by yellow on the plot). The results for the offshore area are consistent with the offshore data points from the UKMO European wave model and the VOS data given in HR Wallingford (1993a & b). The results are also consistent with the wave observations made by CMC at Hurd Bank (CMC, 1995).

The sea area for the lowest specified significant wave height band (1.5m) extends all the way around the islands. The significant wave height that is exceeded for 10% of the year is between 0 and 1.5 (represented by blue on the plot) for a sea area that extends approximately 10km offshore to the north-east of the islands and less than 5km to the south-west.

It should be noted that the two maps (figures 6.7 and 6.8) show the 10%ile significant wave height for the sea areas in which vessels operate, and are not intended to represent conditions caused by localised effects such as reflection from breakwaters.

7. References

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Appendix 1

Quality Statement: UK Met Office Wave Model Archive

The Met Office Wave Model Archive consists of the hindcast fields of winds and waves produced during the operation of the atmospheric and wave model forecast suite. To produce the best possible analysis of surface wind, all available reports of surface pressure, wind speed and direction (from ships, buoys, platforms and land stations) are subjected to a range of consistency checks before being assimilated into the model's analysis. The resulting wind field is then used to modify the wave field derived from earlier timesteps. For each of the 16 directional and 13 frequency bands, the changes in wave energy are computed at each gridpoint, using the local wind as energy input, and allowing for propagation, dissipation and transfer between spectral bands. The model is a so-called 'Second Generation' model, where the spectral shape is empirically defined and then allowed to evolve over time. For further details see Golding (1983) and Francis (1985). There are two versions of the wave model, both in operation since 1986 - one covers the Global oceans and the other European waters.

The **Global Wave Model** initially operated with an assumed fixed depth (200m) on a lat/long grid. The analysed fields of wind and 1-dimensional spectra (ie energy within each spectral band, plus a mean direction for that band) have been archived, initially at 12-hour intervals and subsequently (since June 1988) at 6-hour intervals. The spatial resolution was initially approx 150km (13.8k gridpoints). This was improved in June 1991, to approx 90km (37.3k gridpoints), and yet again in May 1999 to a resolution of around 55km, with depth-dependency. The enhanced resolution now allows sheltered seas (eg Persian Gulf, Caspian Sea) to be covered by the model and narrow waterways (eg Straits of Taiwan) are now handled more realistically.

Nested within the Global Wave Model, and taking boundary conditions from it, is a **European Waters Wave Model**. This is a depth-dependent second-generation model operating on a lat/long grid with spacing approx 25km (8.5k gridpoints). The model covers West European waters to 14degW between 30.5N and 66.7N and also covers the Mediterranean and Baltic Seas; the Black Sea was added in 1993. Wind and wave hindcast values were archived initially at 6-hour intervals and since June 1988 at 3-hour intervals.

Output at each timestep consists of wind speed and direction, plus **either**:

1-dimensional spectrum (energy and mean direction in each of the 13 spectral bands) **or**

the conventional integrated variables derived from the spectrum (ie significant wave height, period and direction for both windsea and swell, together with resultant height and period).

Since the winds are taken from the lowest level of the Atmospheric Model, they represent conditions approx 20m above mean sea level.

As with any operational model, there have been many small-scale improvements incorporated over the years. Most of these are introduced for computational reasons, to improve the efficiency of the calculations, but some are more fundamental, particularly the incorporation of wave height data from the ERS-1 satellite into the Global Wave model analysis with effect from June 1993 (see Foreman et al, 1994). Further detail (and dates) of the more significant changes to the model's operation are available on request. Over the years there have been occasional interruptions to the operational routine due to mainframe malfunction. Consequently, there are some periods of missing data in the archive, most of them of 12 hours duration or less.

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Appendix 2

Verification Of UKMO Wave Models

The archive of wave model hindcasts covers almost all global oceans, with higher space and time resolution over European waters. Although routine verification is carried out against reports from buoy and platform sites, in comparison with the number of model gridpoints available there are very few locations reporting wave observations routinely. For a variety of reasons (including varying water depths and representation of model coastline), a verification at one point may not be applicable even a few gridpoints away. Thus, it is not normally possible to answer the question "How good is the model at my location?"

However, as an indication of the current performance of the UKMO wave model, a comparison has been undertaken against buoy measurements of significant wave height at a location West of Shetland during the months of January and February 1996. (Data provided by courtesy of BP Exploration.) At this location, there were no real-time reports of wind for input into the model, and so the observed data can be considered truly independent. Therefore, this verification might be considered broadly representative of a range of mid-latitude open-ocean locations where no reports are available.

The results over a period of about one month in January/February 1996 are summarised in the two graphs attached - one for the European wave model and one for the Global model. It can be seen that the Correlation Coefficient is 0.96 and the Scatter Index (SI) is less than 15% in both cases. (SI = Root Mean Square Error * 100/Average measured SWH) A SI of less than 20% is generally considered to indicate a very good performance by a wave model.

It is noteworthy that the SI is slightly less for the Global model than for the European model. This may be due to the fact that observations made by the ERS satellite are directly assimilated into the Global model, but only indirectly (via the specification of conditions along the western boundary) into the European model. Given the water depth at this location (190m), shallow water effects are unlikely to be important.

Tables

Table 5.1 Percentage exceedance of offshore wind speed at Point B, Point D and at Malta International Airport. Annual period of operation.

Wind Speed (m/s)	Percentage Exceedance		
	Airport	Point B	Point D
0	100	100	100
2	84	90	91
4	64	71	72
6	37	45	48
8	9	19	21
10	2	7	8
14	0	2	2
18	0	0	0

Table 5.2 Percentage exceedance of offshore wind speed at Point B, Point D and at Malta International Airport. Summer period of operation.

Wind Speed (m/s)	Percentage Exceedance		
	Airport	Point B	Point D
0	100	100	100
2	82	87	88
4	61	63	64
6	31	35	38
8	6	12	14
10	1	4	4
14	0	0	1
18	0	0	0

Table 5.3 Percentage exceedance of offshore significant wave height at Points A-D. Annual period of operation.

Significant Wave Height (m)	Percentage Exceedance			
	Point A	Point B	Point C	Point D
0	100	100	100	100
0.5	68	69	68	70
1	38	38	38	39
1.5	20	21	20	21
2	11	11	11	12
2.5	6	6	6	6
3	3	3	3	3
3.5	1	1	1	2
4	1	1	1	1
4.5	0	0	0	0

Table 5.4 Percentage exceedance of offshore significant wave height at Points A-D. Summer period of operation.

Significant Wave Height (m)	Percentage Exceedance			
	Point A	Point B	Point C	Point D
0	100	100	100	100
0.5	56	56	57	57
1	26	26	27	27
1.5	12	12	13	13
2	6	6	6	6
2.5	3	2	3	3
3	1	1	1	1
3.5	0	0	0	0

Table 6.1 Nearshore NSW model verification. Comparison of model predictions between HR Wallingford (1996), Svasek (1998) and Scott Wilson for a point just west of Cirkewwa at -30mCD

Offshore Wave Direction (°N)	Offshore Significant Wave Height (m)	HRW Inshore Significant Wave Height (m)	Svasek Inshore Significant Wave Height (m)	SW Inshore Significant Wave Height (m)	HRW Inshore Wave Direction (°N)	Svasek Inshore Wave Direction (°N)	SW Inshore Wave Direction (°N)
240	2.9	2.2		2.7	249		246
270	4.6	3.1	4.4	3.5	259	271	259
300	6	2.9		3.5	266		271

Table 6.2 Nearshore NSW model verification. Comparison of model predictions between HR Wallingford (1991) and Scott Wilson for a point just east of Valletta, offshore of the St Elmo breakwater at -10mCD.

Offshore Wave Direction (°N)	Offshore Significant Wave Height (m)	HRW Inshore Significant Wave Height (m)	SW Inshore Significant Wave Height (m)	HRW Inshore Wave Direction (°N)	SW Inshore Wave Direction (°N)
60	4.2	3.7	3.6	49	58
90	4.2	3.2	3.1	59	68
120	4.0	2.2	2.5	75	85

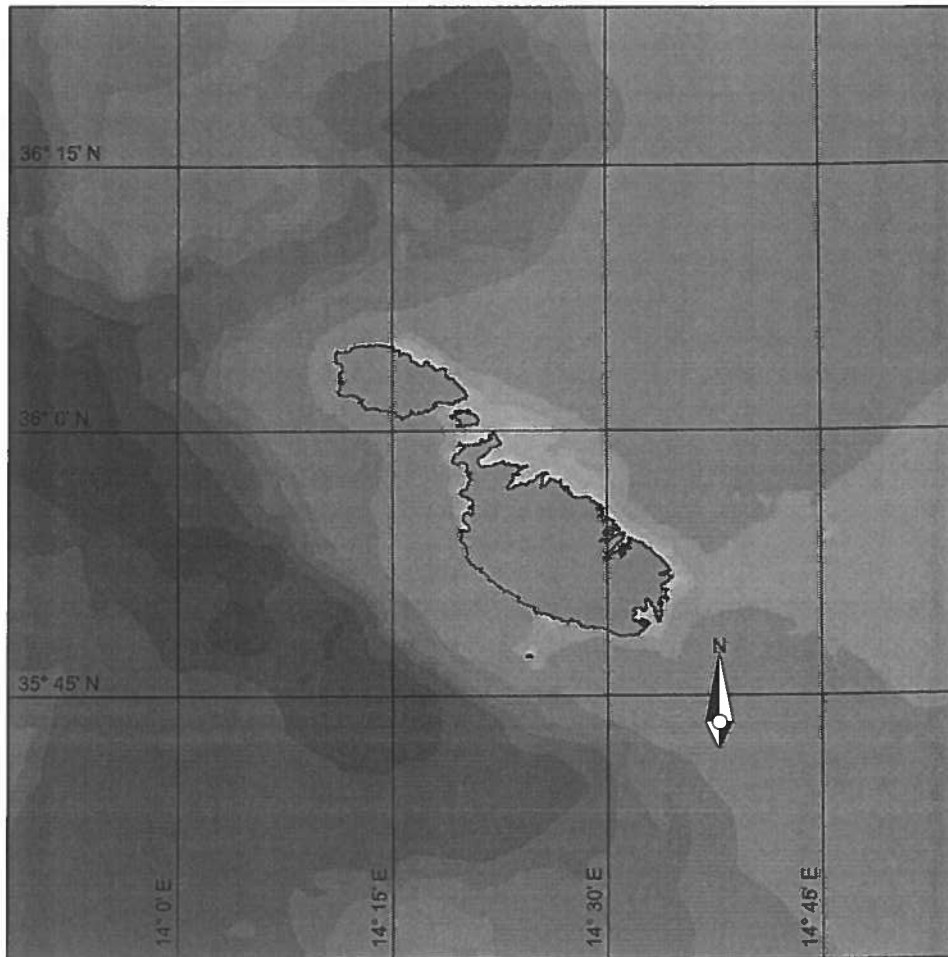


Figure 1.1 Location map.

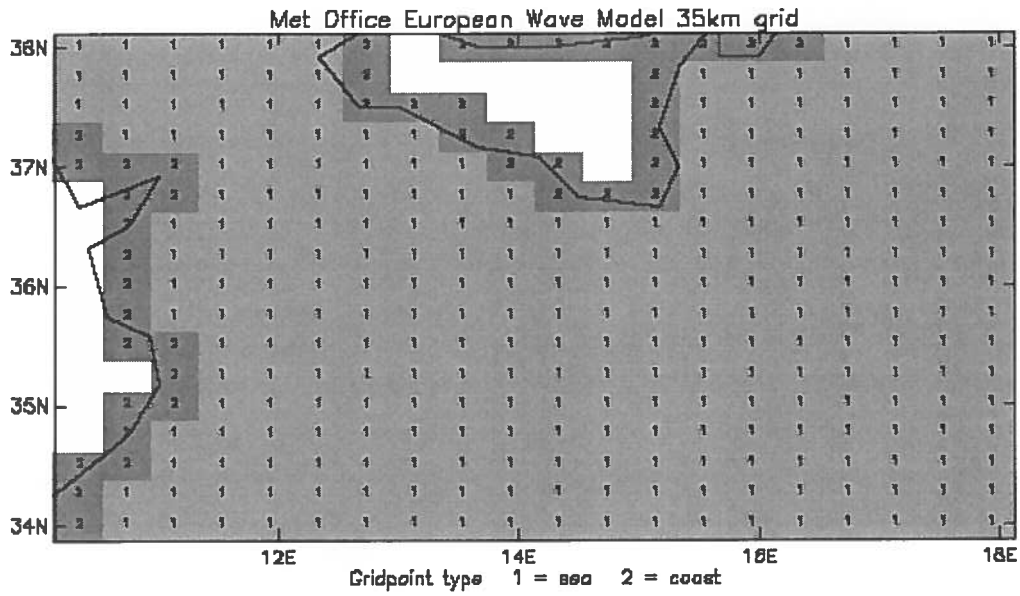


Figure 3.1 UKMO European Wave Model Grid in the area around Malta

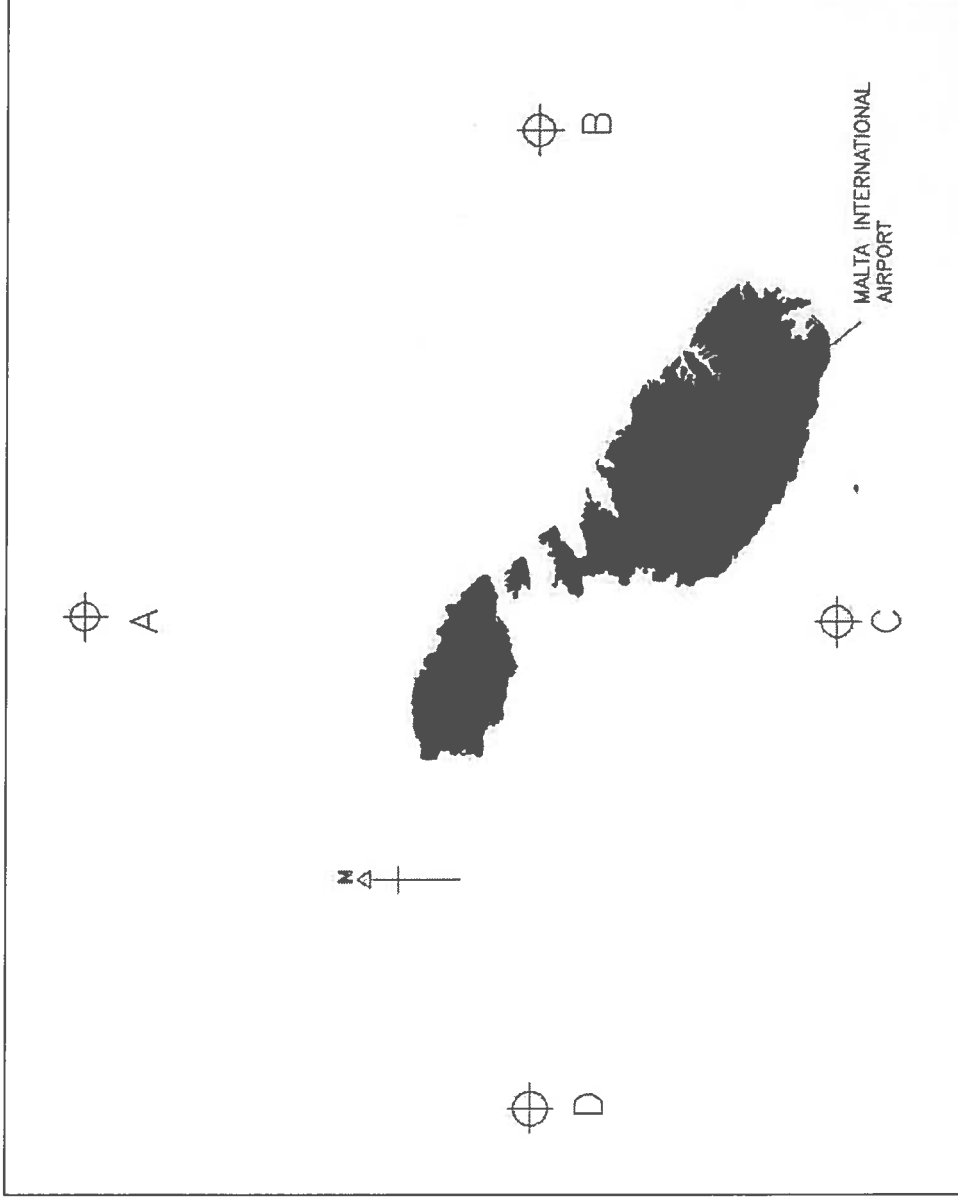


Figure 5.1 Location map for offshore wind/wave data points and Malta International Airport.

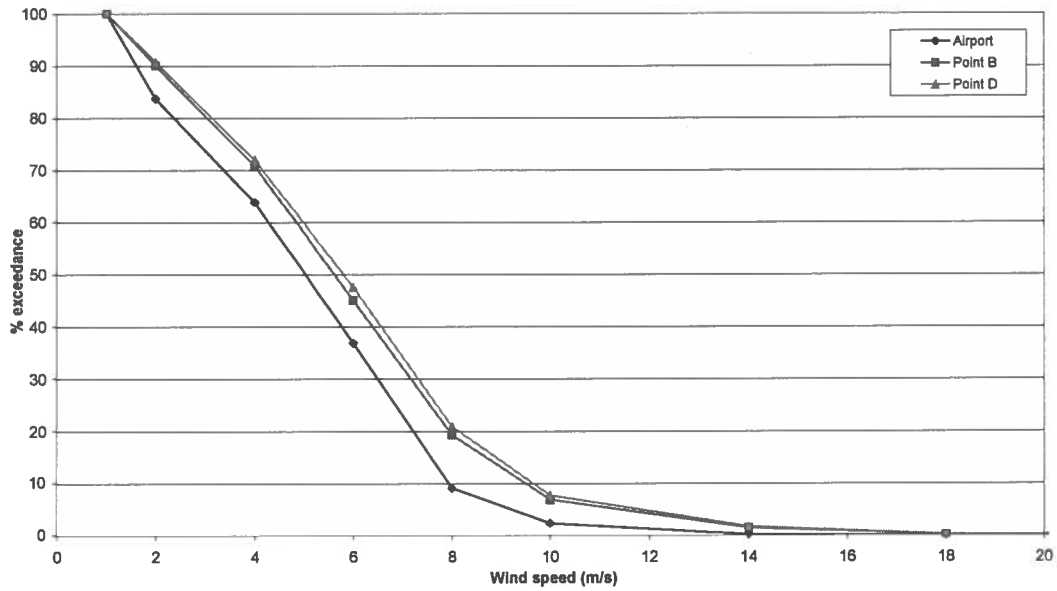


Figure 5.2 Wind speed percentage exceedance for the annual period of operation

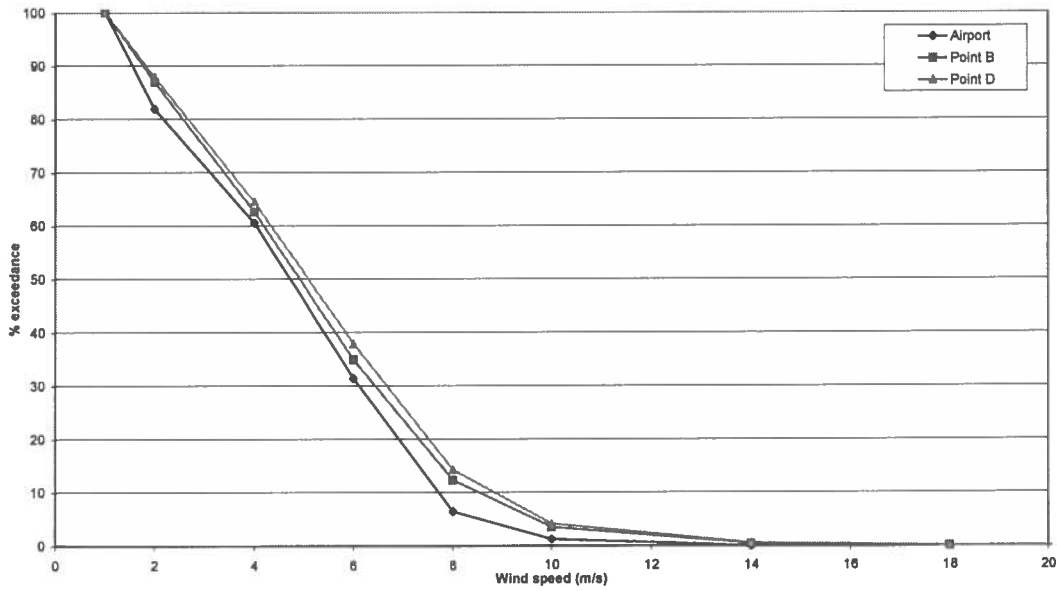


Figure 5.3 Wind speed percentage exceedance for the summer period of operation

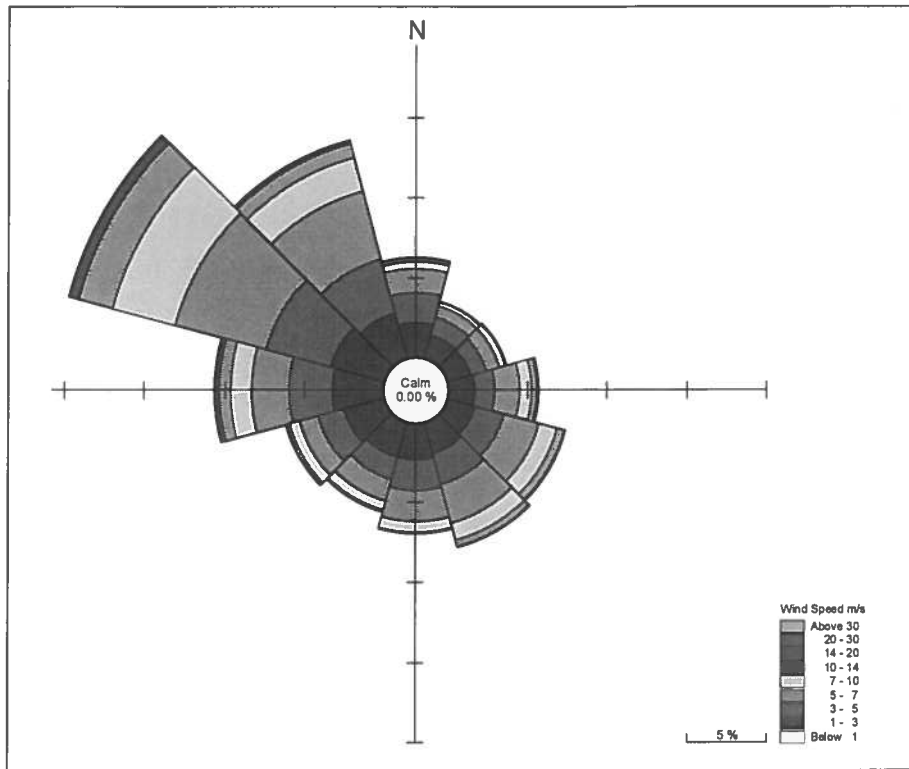


Figure 5.4 Offshore wind rose at Point D for the annual period of operation.

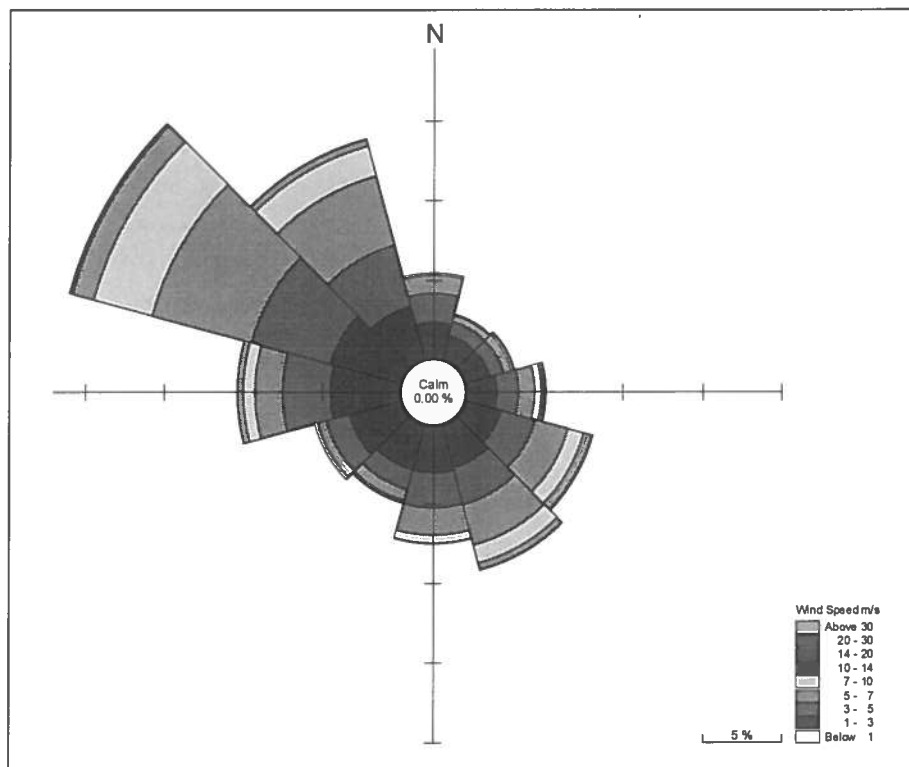


Figure 5.5 Offshore wind rose at Point D for the summer period of operation.

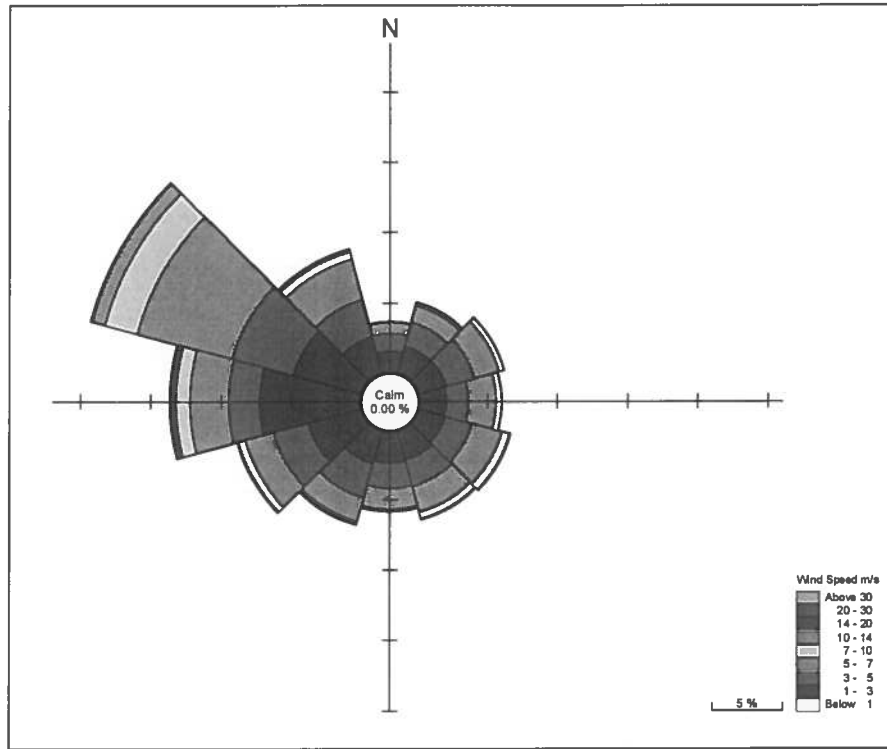


Figure 5.6 Wind rose at Malta International Airport for the annual period of operation.

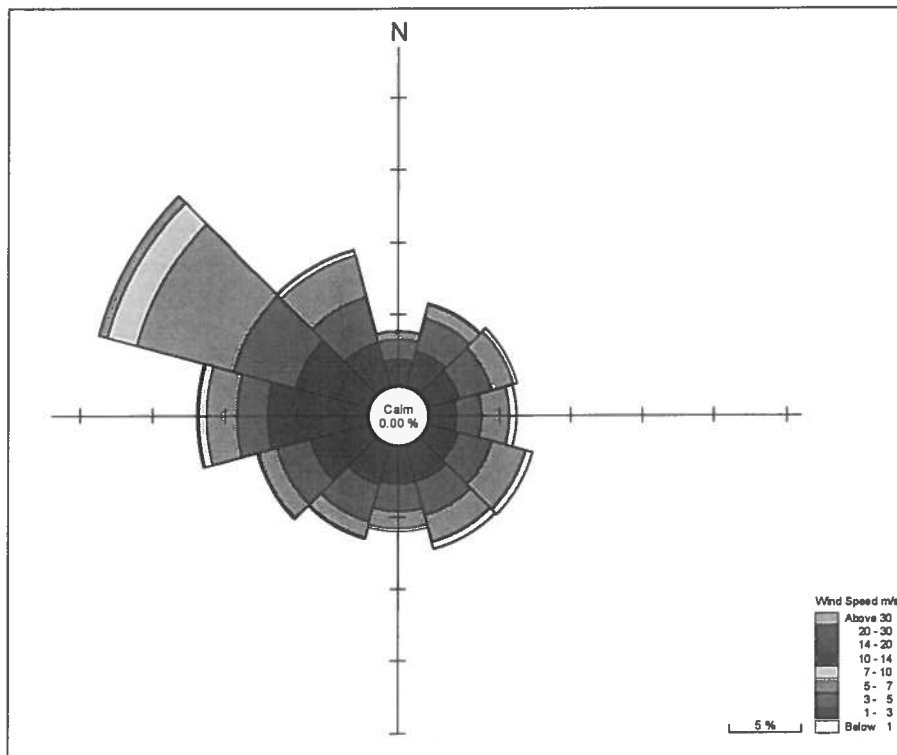


Figure 5.7 Wind rose at Malta International Airport for the summer period of operation.

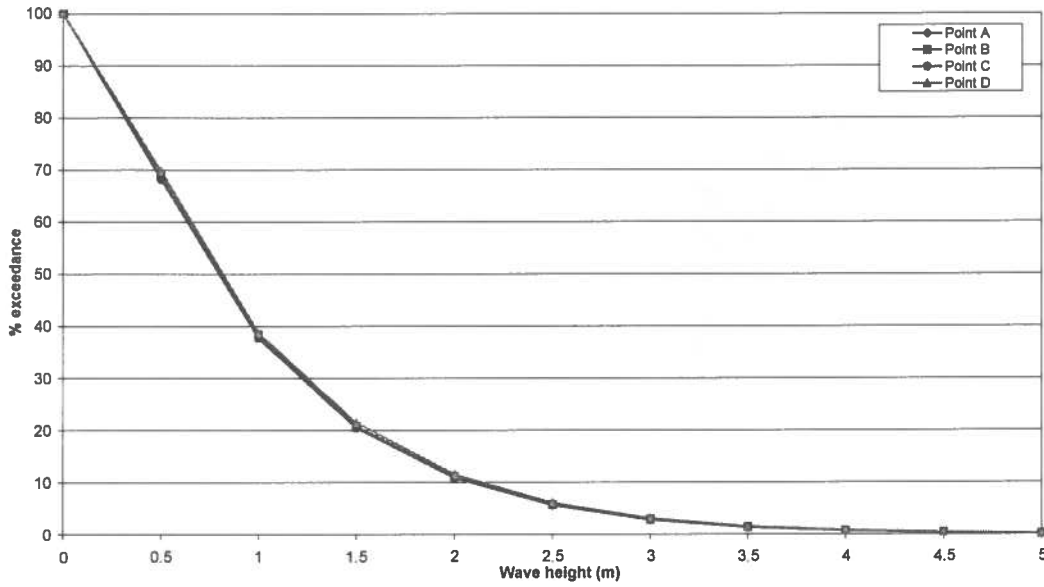


Figure 5.8 Significant wave height percentage exceedance for the annual period of operation. Source: UKMO European Wave Model.

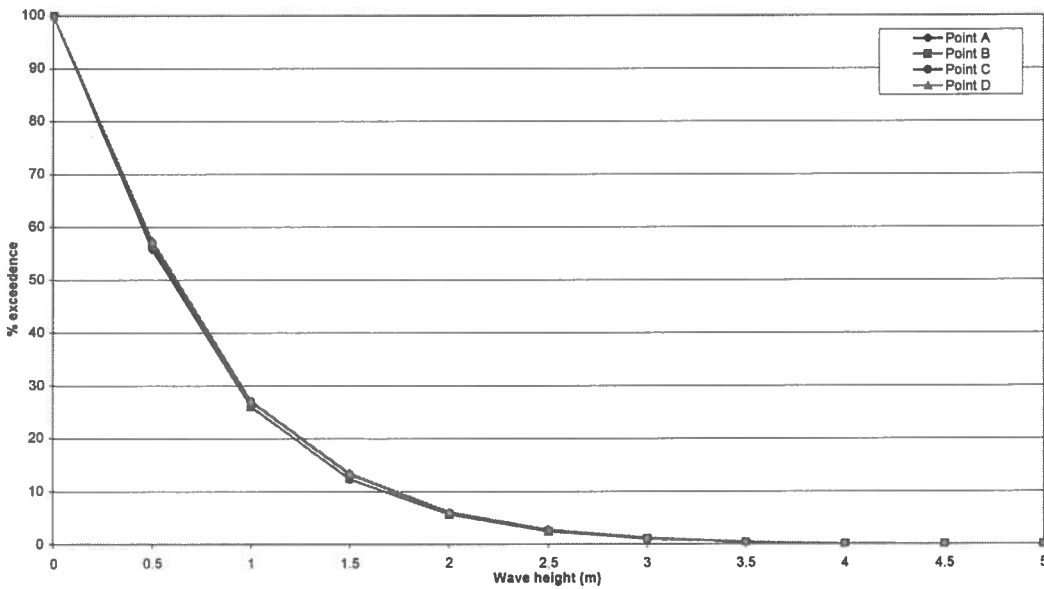


Figure 5.9 Significant wave height percentage exceedance for the summer period of operation. Source: UKMO European Wave Model.

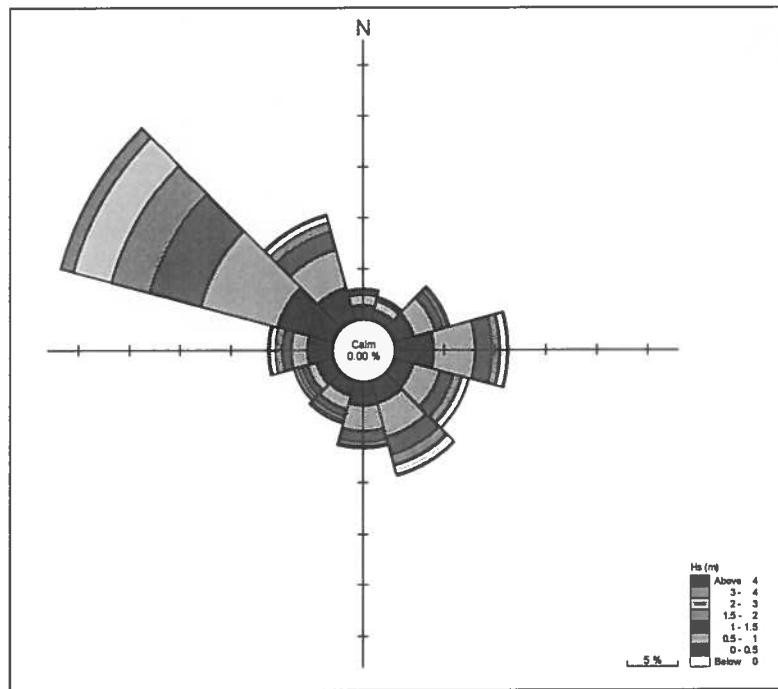


Figure 5.10 Offshore significant wave height rose – Point D for the annual period of operation. Source: UKMO European Wave Model.

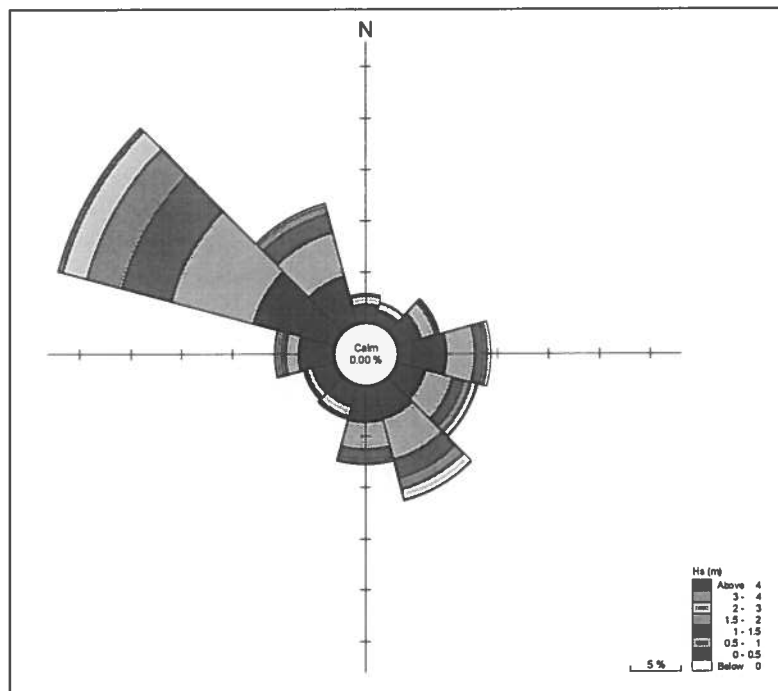


Figure 5.11 Offshore significant wave height rose – Point D for the summer period of operation. Source: UKMO European Wave Model.

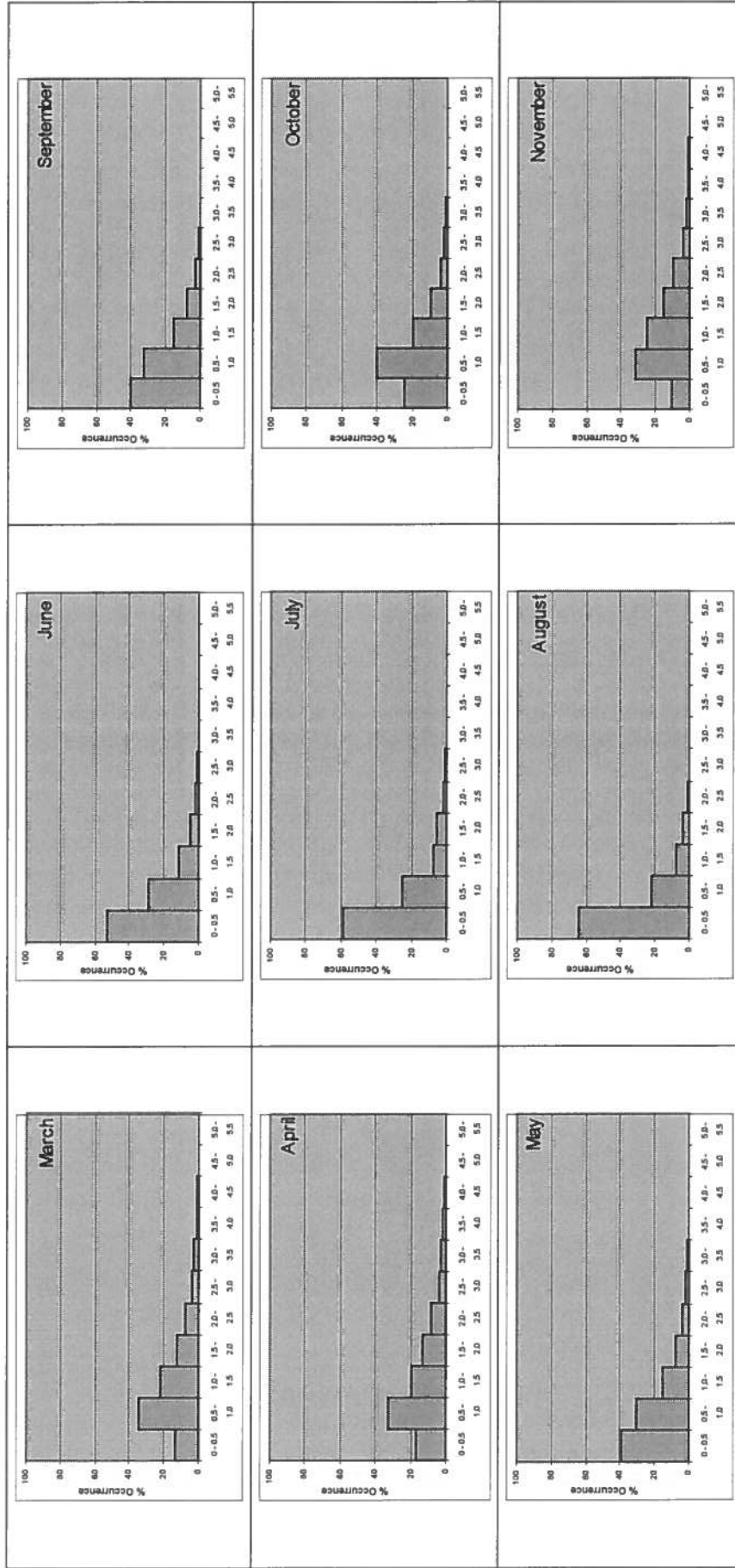


Figure 5.12 Significant Wave height distribuion for offshore Point D between the months March to November. Source: UKMO wave model 1988-2002.

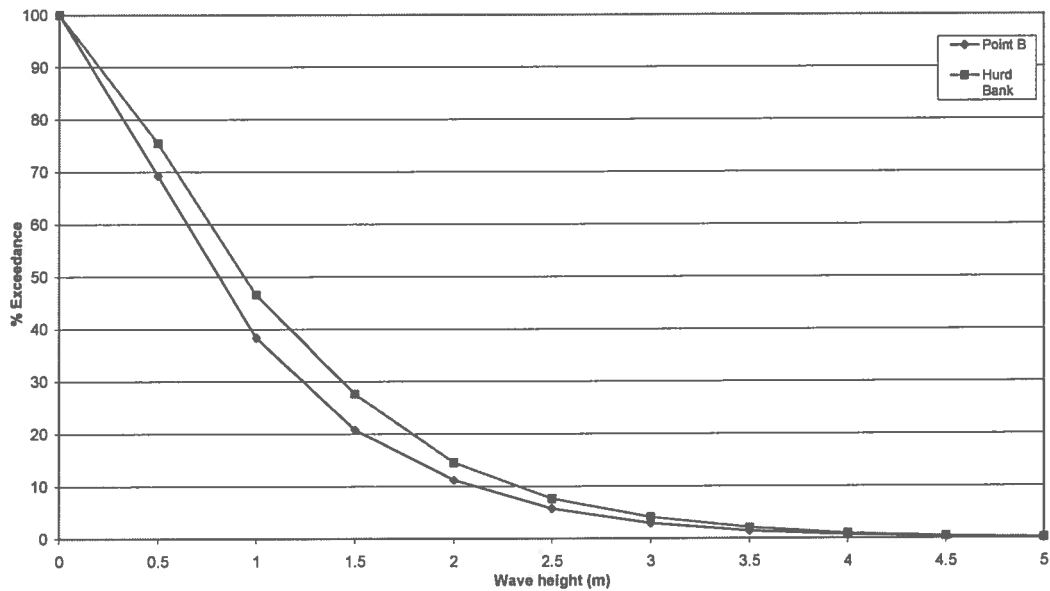


Figure 5.13 Comparison between wave statistics from the Hurd Bank wave buoy 1992-1994 (CMC, 1995) and UKMO Point B 1988-2002 for the annual period of operation

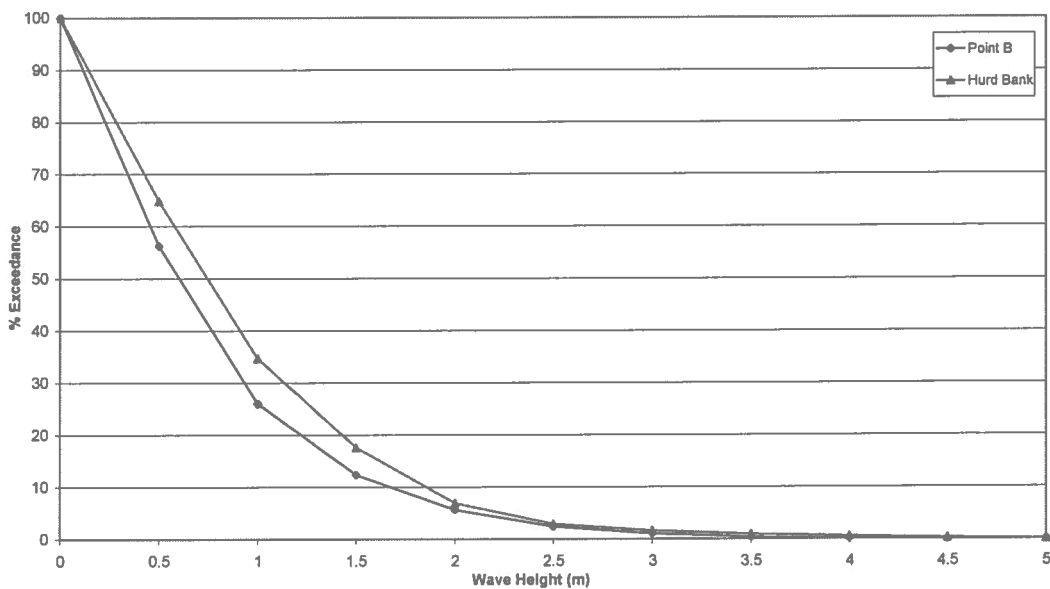


Figure 5.14 Comparison between wave statistics from the Hurd Bank wave buoy 1992-1994 (CMC, 1995) and UKMO Point B 1988-2002 for the summer period of operation

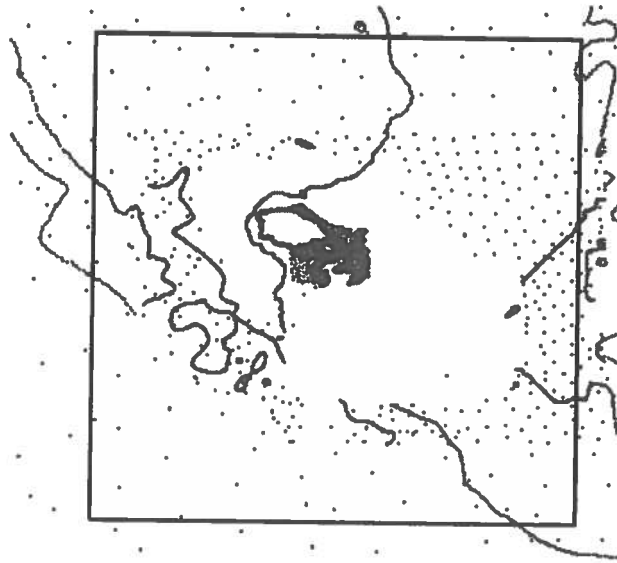


Figure 6.1 Digitised seabed contours and spot heights from Admiralty charts around Malta

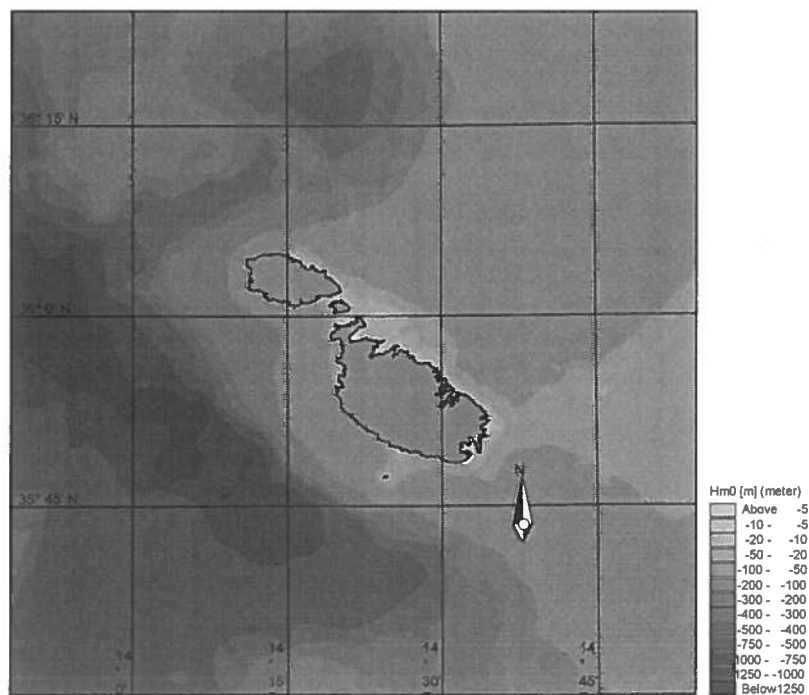


Figure 6.2 NSW model bathymetry

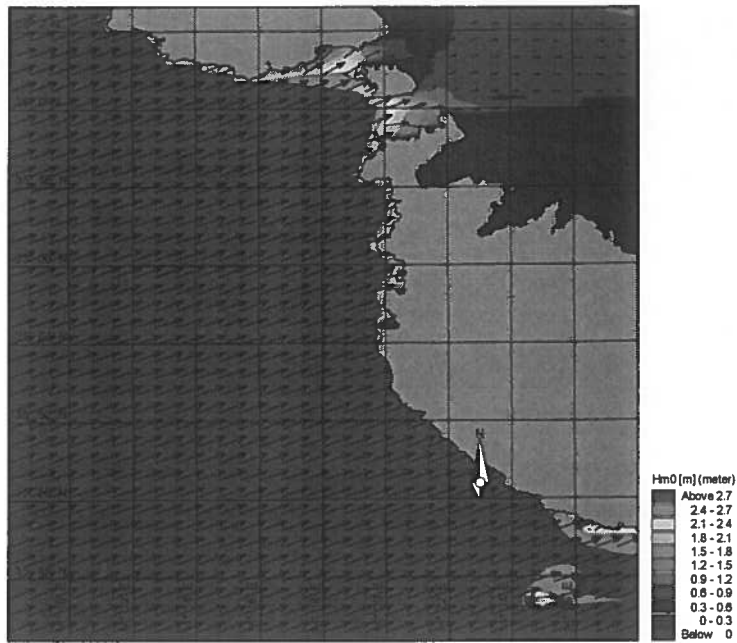


Figure 6.3 NSW model verification, 1-year return period wave conditions. Offshore incident wave direction 240° and significant wave height 2.9m. Colour contours represent significant wave height and vectors represent wave direction.

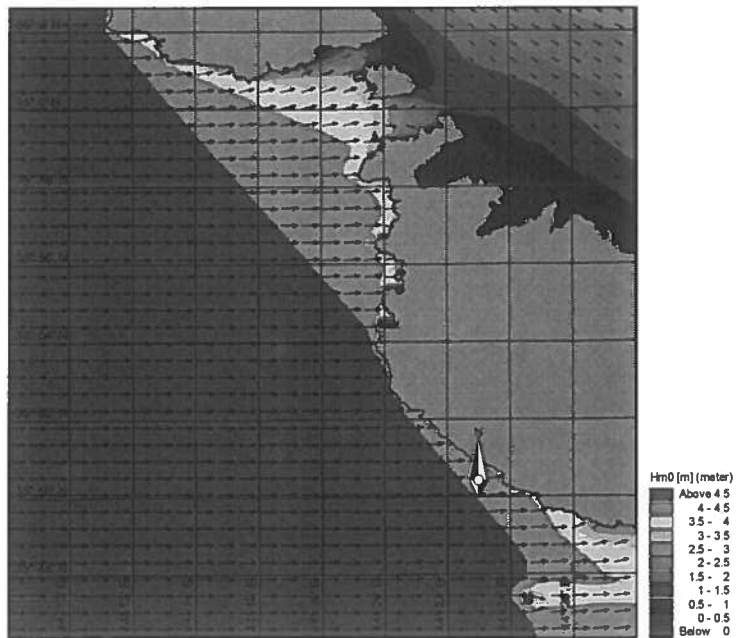


Figure 6.4 NSW model verification, 1-year return period wave conditions. Offshore incident wave direction 270° and significant wave height 4.6m.

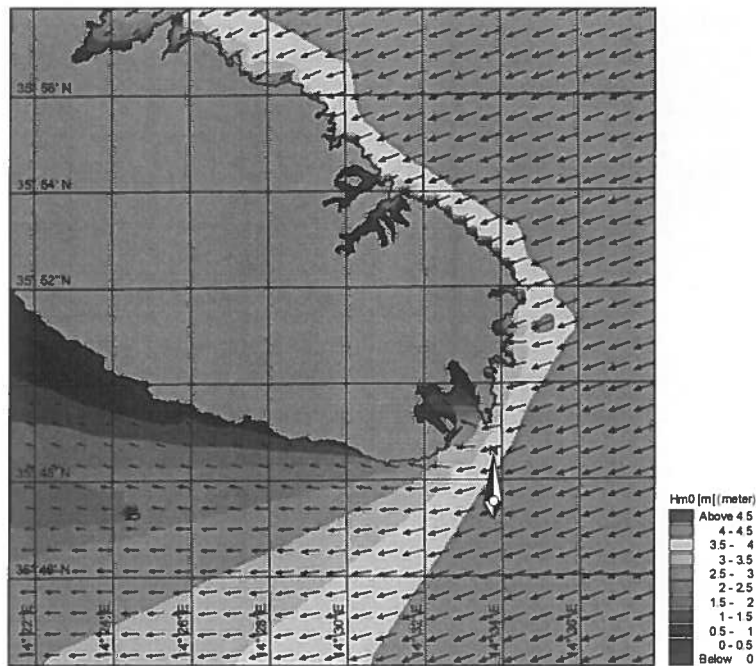


Figure 6.5 NSW model verification, 1-year return period wave conditions. Offshore incident wave direction 60° and significant wave height 4.2m.

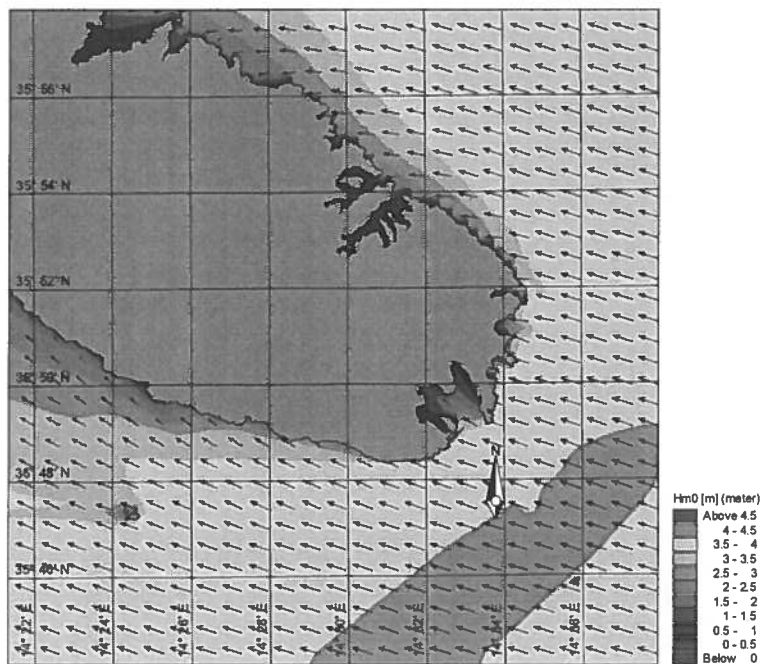


Figure 6.6 NSW model verification, 1-year return period wave conditions. Offshore incident wave direction 120° and significant wave height 4.0m.

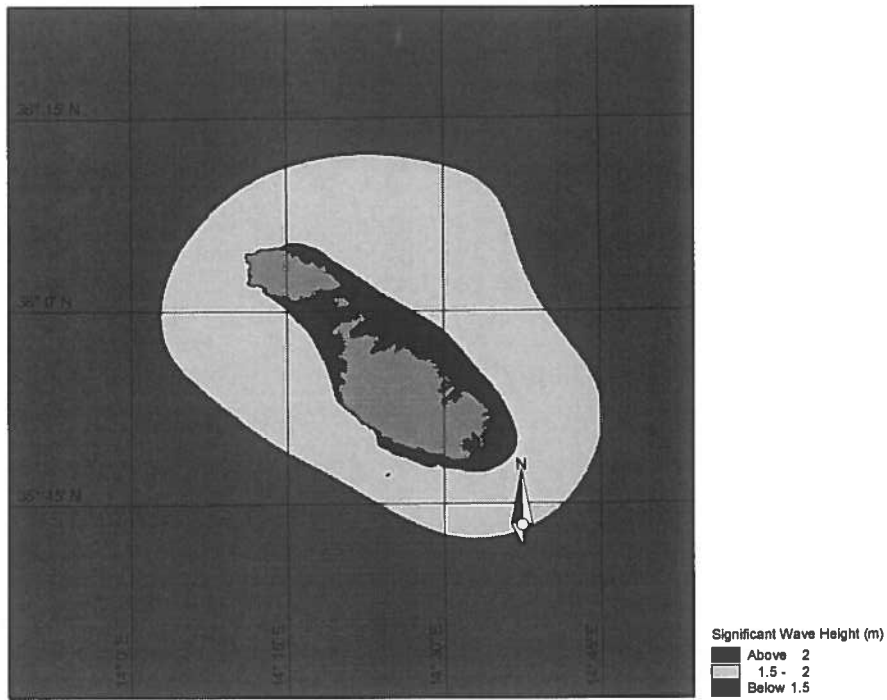


Figure 6.7 Sea areas where the Significant Wave Height is exceeded for 10% of the year.

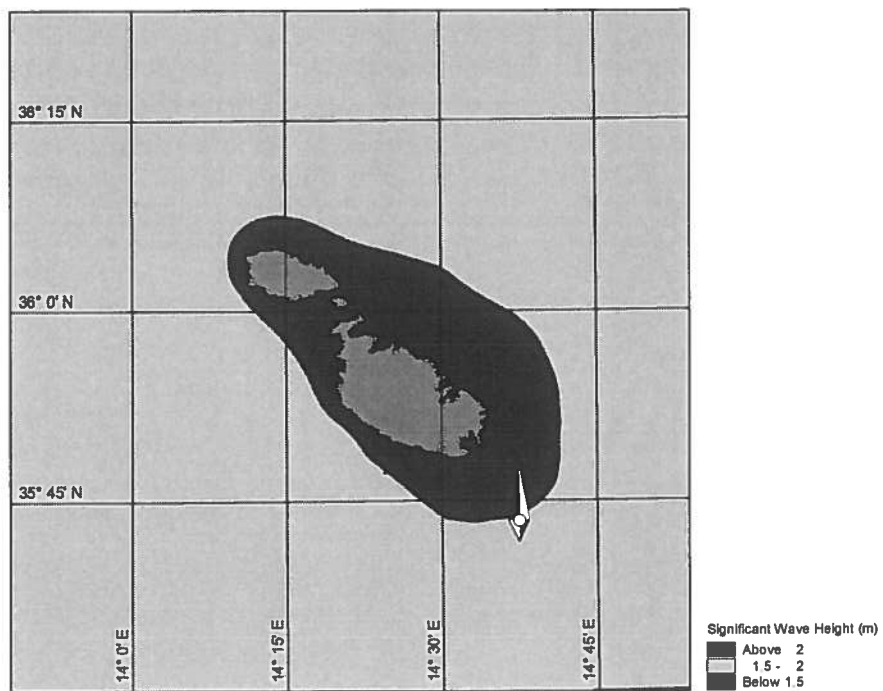


Figure 6.8 Sea areas where the Significant Wave Height is exceeded for 10% of the summer period of operation (April to October inclusive).

