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# IRISH COASTAL WAVE AND WATER LEVEL MODELLING STUDY 2018

## Phase 2 – Coastal Areas Potentially Vulnerable to Wave Overtopping



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Phase 2  
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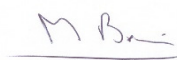
## PHASE 2 TECHNICAL REPORT

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### Approval for issue

Malcolm Brian



24 March 2021

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# Contents

<b>EXECUTIVE SUMMARY</b>	<b>1</b>
<b>1 INTRODUCTION</b>	<b>2</b>
<b>2 KEY INFORMATION ON STUDY OUTPUTS</b>	<b>4</b>
<b>3 DATA SOURCES</b>	<b>6</b>
3.1 Wave and Wind Data	6
3.2 Bathymetric Data	8
3.3 Water Level Data	8
<b>4 STATISTICAL ANALYSIS</b>	<b>11</b>
4.1 Extreme Value Analysis	13
4.2 Joint Probability Analysis	13
4.2.1 Correlation Coefficients	13
<b>5 MODEL DEVELOPMENT AND SIMULATION</b>	<b>15</b>
5.1 Modelling System	15
5.2 Model Bathymetries	15
5.3 Model Simulations	20
<b>6 IMPACT OF SEA LEVEL RISE</b>	<b>23</b>
<b>7 MEAN SEA LEVEL TO OD MALIN CONVERSION</b>	<b>24</b>
<b>8 RESULTS AND STUDY OUTPUT</b>	<b>25</b>
<b>9 REFERENCES</b>	<b>29</b>
<b>10 GLOSSARY OF TERMS</b>	<b>30</b>

## Tables

Table 1-1: Coastal Areas Potentially Vulnerable to Wave Overtopping (CAPO)	2
Table 3-1: Increase in Storminess Assessment – Factors per Directional Sector at UK Met Office	
Wave Data Points	8
Table 3-2: Source of Water Level Data for Phase 2 Wave and Water Level Modelling	10
Table 4-1: Joint Probability Variables required for each CAPO	12
Table 4-2: Derived Correlation between Offshore Wave Heights and Water Levels	14
Table 5-1: Critical Directions simulated for Combined, Swell and Wind waves for each CAPO	22
Table 6-1: Sea Level Rise for various Future Scenarios	23
Table 8-1: Sample Output for Wicklow	26
Table 8-2: List of Appendices by Study Area	28

## Figures

Figure 3.1: ECMWF and UK Met Office Offshore Wave Data Points	7
Figure 4.1: Example of Wave Rose on North West Coast at Point 55.5°N, 10.0°W (ECMWF ERA 5 Combined Significant Wave Height)	11
Figure 5.1: North East Coast Model Extent and Bathymetry (to MSL)	16
Figure 5.2: South East Coast Model Extent and Bathymetry (to MSL)	16
Figure 5.3: South Coast Model Extent and Bathymetry (to MSL)	16
Figure 5.4: Cork Harbour Model Extent and Bathymetry (to MSL)	17
Figure 5.5: South West Coast Model Extent and Bathymetry (to MSL)	17
Figure 5.6: West Coast Model Extent and Bathymetry (to MSL)	18

## PHASE 2 TECHNICAL REPORT

Figure 5.7: Galway Bay Model Extent and Bathymetry (to MSL) .....	18
Figure 5.8: Shannon Estuary Model Extent and Bathymetry (to MSL) .....	19
Figure 5.9: North West Coast Model Extent and Bathymetry (to MSL) .....	19
Figure 5.10: North Coast Model Extent and Bathymetry (to MSL) .....	20
Figure 5.11: Lough Foyle Model Extent and Bathymetry (to MSL) .....	20
Figure 8.1: Sample Estimation Location Plot for Wicklow .....	27

## Appendices

**Appendix A** – Wave Rose Plots of Offshore Wave Data

**Appendix B** - Extreme Value Analysis of Offshore Wave / Wind Data

**Appendix C** - Joint Probability Analysis of Wave / Wind data and Inshore Water Level

**Appendix D** - Combinations of estimated inshore wave and water level conditions for the East Coast

**Appendix E** - Combinations of estimated inshore wave and water level conditions for the South East Coast

**Appendix F** - Combinations of estimated inshore wave and water level conditions for Cork Harbour

**Appendix G** - Combinations of estimated inshore wave and water level conditions for the South West Coast

**Appendix H** - Combinations of estimated inshore wave and water level conditions for the West Coast

**Appendix I** - Combinations of estimated inshore wave and water level conditions for the Shannon Estuary

**Appendix J** - Combinations of estimated inshore wave and water level conditions for the North West Neagh Bann Coast

## EXECUTIVE SUMMARY

This report presents the work undertaken and the findings of Phase 2 of the Irish Coastal Wave and Water Level Modelling Study (ICWWS) 2018. The Phase 2 results provide an update to the wave climate and water level combinations of known Annual Exceedance Probability (AEP) originally presented as output from the Irish Coastal Wave and Water Level Modelling Study (ICWWS) 2013 for specific flood risk locations considered vulnerable to wave overtopping, Coastal Areas Potentially Vulnerable to Overtopping (CAPOs).

Overtopping of existing defences and coastal structures (both manmade and natural) as a consequence of the interaction of waves and sea level conditions, including tide and surge, may contribute to coastal flooding in areas located behind these defences. To derive overtopping volumes or rates, wave climate conditions for various water levels at the shoreline or defence line are required.

For this study, a series of numerical models were used to transform offshore combined waves of known AEP to near the shoreline or defence line, or in cases where local wind waves were dominant, numerical models were used to simulate the local generation of the wind waves. The relevant offshore wave climate conditions or wind speeds were combined with present day water levels using a joint probability analysis. These combinations were then used as input to the numerical models. The current study provides an update to the ICWWS 2013 based on the inclusion of additional offshore wave data, along with the use of updated extreme water levels, derived during Phase 1 of this study.

Combinations of present day wave climate (heights, periods and directions) and water levels for AEPs of 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% were derived for the shoreline / defence line in each of the CAPOs considered in the 2013 study. A similar approach was undertaken in order to determine the corresponding wave climate and water levels for four future scenarios accounting for different projected sea level rise allowances. Spectral significant wave heights, peak spectral wave periods and mean wave directions for each AEP and water level at a series of shoreline / defence line locations representing CAPOs comprise the key outputs of this study.

Whilst the outputs of this phase of the study are considered suitable for the assessment of flood risk at a community level, they are not suitable for the assessment of flood risk to individual sites or properties, the detailed assessment of existing coastal infrastructure, or for the design of new coastal infrastructure.

# 1 INTRODUCTION

Overtopping of existing defences and coastal structures (both manmade and natural) due to the interaction of wave and sea level conditions, including tide and surge, may contribute to coastal flooding in areas located behind these defences. This study follows on from the 2013 Irish Coastal Wave and Water Level Modelling Study (ICWWS) (Reference 1), where a screening analysis identified a number of areas around the coast of Ireland which were considered to be potentially at significant risk from coastal flooding due to wave overtopping for both the present day and future sea level scenarios. Coastal Areas Potentially Vulnerable to Wave Overtopping (CAPOs) were selected based on three key elements; the presence of low-lying areas with the potential for significant coastal inundation, potential exposure to significant offshore storm (swell) waves or locally generated wind waves and the presence of notable assets within the potential flood extents. Table 1-1 lists the CAPOs selected for analysis within the 2013 study, grouped by Catchment Flood Risk Assessment and Management (CFRAM) Programme study area.

**Table 1-1: Coastal Areas Potentially Vulnerable to Wave Overtopping (CAPO)**

Study Area	East	South East	Cork Harbour	South West	Shannon	West	North West Neagh Bann
Coastal Areas Potentially Vulnerable to Wave Overtopping (CAPO)	Bettystown	Kilbegnet	Cobh	Youghal	Tralee	Ballyvaghan	Tullaghan
	Skerries	Cahore		Castletownbere	Ballyheige	Dungory	Rosstownlagh
	Malahide	Wexford		Kenmare	Tarbert	Galway	Killybegs
	Portmarnock	Burrow		Assroe	Foynes	Spiddle	Dunfanaghy
	Howth	Rosslare Strand		Waterville	Coonagh	Westport	Downings
	Sutton	Arthurstown		Dingle	Shannon	Belmullet	Rathmullan
	Dublin	Whitewall			Kilrush	Strandhill	Letterkenny
	Bray	Dungarvan			Kilkee	Sligo	Buncrana
	Ballydonarea	Ardmore			Creggane		Moville
	Blackditch				Lahinch		Omeath
	Wicklow						Carlingford
	Arklow						Greenore
							Ballynamony
							Dundalk
							Annagassan
							Dunany
							Cruisetown

Knowledge of wave heights and periods associated with various water levels at the shoreline or defence line for a range of annual exceedance probability (AEP) events is required to facilitate the calculation of overtopping volumes or rates. The focus of the ICWWS 2013 was to provide sufficient information on combinations of waves and water levels of known exceedance probability for strategic assessment of the flood risk at locations considered vulnerable to wave overtopping. This study provides an update on the wave and water level conditions at the above locations, based on the inclusion of additional years of data collated since the previous study within the offshore wave analysis, and the use of updated extreme water levels, derived during Phase 1 of this study, but does not provide any increased detail. The number of years of additional data incorporated depended on the source of the data and its availability during both the ICWWS 2013 and ICWWS 2018. In general, locations outside of the Irish Sea included an additional 7 to 8 years of data from 2012/2013 to 2019, depending on location. CAPOs within the Irish Sea made use of a different dataset than for the ICWWS 2013 which included data up to and including 2018, as discussed in Section 3.1.

The offshore wave climate used to determine wave conditions along the CAPO shorelines or defence lines was established using extreme value analysis and joint probability analysis of present day water levels with wave heights or wind speeds, depending on the relative significance of offshore storm waves and locally generated wind waves at the CAPO. Output from the extreme value analysis and joint probability analysis provided input conditions to a series of computational models based on the MIKE Spectral Wave (SW) Flexible Mesh module developed by the Danish Hydraulic Institute (DHI). These simulations transformed offshore combined waves to near the shoreline or defence line, or in the case of fetch limited models, simulated the local generation of wind waves.

## PHASE 2 TECHNICAL REPORT

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Whilst the outputs of this study are considered suitable for the assessment of flood risk at a community level, they are not considered suitable for the assessment of flood risk to individual sites or properties, the detailed assessment of existing coastal infrastructure, or for the design of new coastal infrastructure.

Updated, combinations of present day wave climate conditions (heights, periods and directions) and water levels for AEPs of 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% were derived for the majority of the shorelines / defence lines identified as CAPOs in the ICWWS 2013 study. Some of the CAPOs identified during the ICWWS 2013 have been identified for more detailed studies under Phase 3 of the ICWWS 2018, namely Dundalk, Carlingford, Tralee, Shannon and part of Coonagh (replaced with Bunratty). As such, these areas were not included within Phase 2, as the outputs would be superseded by the results of the more detailed Phase 3 assessment.

A similar approach was undertaken in order to determine the corresponding wave climate conditions and water levels for four future scenarios accounting for different projected sea level rise allowances. Spectral significant wave heights, peak spectral wave periods and mean wave directions for each AEP and water level at a series of inshore locations (CAPOs) comprise the key outputs of this study.



## 2 KEY INFORMATION ON STUDY OUTPUTS

The Phase 2 study outputs include combinations of wave climate and extreme sea level estimates for a series of shoreline / defence line locations at Irish coastal areas considered potentially vulnerable to wave overtopping. These outputs are based on analysis and modelling, including:

- Statistical extreme value analysis and joint probability analysis of offshore wave and wind data and inshore water levels at ICPSS / ICWWS 2018 coastal boundary estimation points.
- Numerical Modelling to transform offshore combined waves to the shoreline / defence line or to simulate the formation of wind waves.

The following key information should be taken into consideration in conjunction with the study outputs/results.

- 1) Combinations of wave climate and water level estimates have been produced at each shoreline / defence line location. These combinations are joint probability occurrences, in which the two elements, wave climate and water level are likely to simultaneously occur for a given AEP. This represents the probability of a combined wave climate and water level event of this, or greater, severity occurring in any given year. For example, a 0.5% AEP event has a 0.5% probability (or 1 in 200 chance) of occurring or being exceeded in any one year.
- 2) For each AEP from 50% to 0.1%, six combinations of waves and water levels were produced representing the complete joint probability range.
- 3) Wave climate and water level combinations were derived for present day sea levels, the Mid-Range Future Scenario (MRFS), High End Future Scenario (HEFS), High+ End Future Scenario (H+EFS) and High++ End Future Scenario (H++EFS) which represent a 0.5m, 1.0m, 1.5m and 2.0m increase in sea level, respectively. These future scenario results do not account for any potential changes to the meteorological systems which may affect the offshore wave climate or wind speeds.
- 4) The wave climate and water level combinations output from the study are representative of a location situated at approximately half the shallow water wavelength seaward from the toe of the defence structure or shoreline.
- 5) Wave climate conditions are presented in terms of spectral significant wave height ( $H_{m0}$ ) in metres, spectral peak wave period ( $T_p$ ) in seconds and mean wave direction (MWD) in degrees measured from North. The  $H_{m0}$  is representative of the mean of the highest third of the waves, whilst  $T_p$  is associated with the most energetic wave in the spectrum.
- 6) The extreme water levels refer to total water levels, which include the effects of astronomic tides and storm surge residual. Astronomic tides are the daily change in sea levels due to the rotation of the earth and the gravitational forces of the sun and moon along with the hydrodynamic response to the bathymetry, whilst storm surge residual refers to the change in sea level caused by the effect of atmospheric pressure variations and persistently strong winds.
- 7) The extreme water levels are also inclusive of local wind set-up or seiching, where abrupt changes in meteorological conditions, such as the passage of an intense depression, may cause oscillations in sea level (or seiches).
- 8) The extreme water levels do not account for any additional set-up which may arise due to the effects of wave action (wave set-up effect).
- 9) The extreme water levels are produced to Mean Sea Level (MSL) and Ordnance Datum Malin (OD Malin) OSGM02 and OSGM15. Mean Sea Level refers to the average sea surface level of all tides over a period of time, whilst OD Malin is the vertical land levelling datum currently used in Ireland, based on the mean sea level recorded between January 1960 and December 1969 at Malin Head tide gauge. This is propagated across the country via the spatial surfaces of the transformation models



## PHASE 2 TECHNICAL REPORT

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OSGM02 and OSGM15 produced by the Ordnance Survey of Great Britain (OS), Ordnance Survey Ireland (OSi) and Land & Property Services.

- 10) Although widely accepted methods have been used to derive the combinations of extreme wave climate and water levels, there are a number of limitations which should be considered when using this data for subsequent analysis. These include uncertainties in the derivation of the individual extreme values associated with topographic and other survey data uncertainties, inaccuracy in meteorological and offshore wave data, assumptions and / or approximations in the hydraulic / hydrodynamic models in representing physical reality, assumptions and / or approximations in the statistical analysis and uncertainties in datum conversions. Further uncertainty arises from the use of the FD2308 joint probability method in the absence of defined and agreed dependence values for waves and tidal levels around Ireland. Further detail on the uncertainties associated with the derivation of extreme tidal levels is given in Reference 2.
- 11) Whilst the outputs of this study are considered suitable for the assessment of flood risk at a community level, they are not considered suitable for the assessment of flood risk to individual sites or properties, the detailed assessment of existing coastal infrastructure or for the design of new coastal infrastructure.

## **3 DATA SOURCES**

### **3.1 Wave and Wind Data**

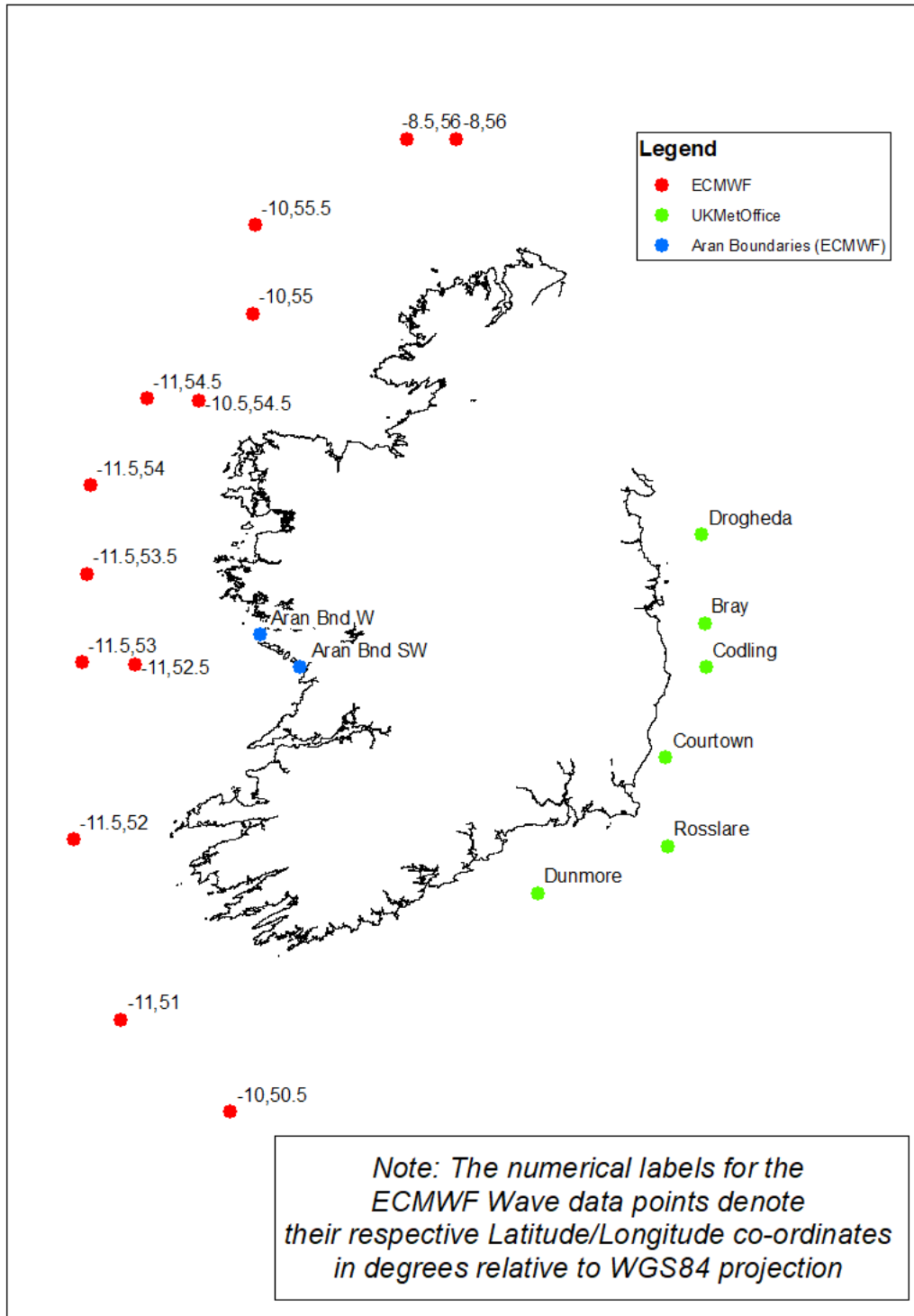
In order to determine appropriate wave and wind conditions for use in the computational modelling for the CAPOs, RPS referred to several datasets. The models along the western and northern coastlines made use of 3 hourly offshore wave data, principally based on output from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global model. Wave data from the most recent 15 years was utilised for the final analysis, to ensure any increase in storminess in the data was adequately captured. The data was directionally discretised and analysed to create profiles of the wave climate in the relevant offshore areas. These profiles were subsequently used to provide boundary conditions for the various wave models.

In the Irish Sea the ICWWS 2013 analysis employed 3 hourly wind and wave data from the UK Met Office's European and UK Waters Wave Model. For the current study, additional UK Met Office hindcast data was sourced from the newer WAVEWATCH III model, however when compared with the original data, and records from the M2 Buoy in the Irish Sea, it was noted that the newer dataset appeared to underestimate some of the peaks in the significant wave heights. As the original UK Met Office model data was unavailable for the update period, RPS made use of the most recent 15 years of WAVEWATCH III model data to inform an assessment of the increase in storminess for each relevant directional sector at various locations in the Irish Sea. These storminess factors were then applied to the original UK Met Office data, to uplift the data where appropriate. For Rosslare and Dunmore East, the ICWWS 2018 update made use of the ECMWF ERA5 model data, to supplement the older UK Met Office model data used in the 2013 study as these locations were not considered to be within the complex Irish Sea basin.

Figure 3.1 shows the locations of the various ECMWF and UK Met Office points used to drive the boundary conditions for the models around the coast of Ireland. As discussed in Section 5.2, timeseries ECMWF wave data was transferred from offshore to the Aran Islands to drive a local model of Galway Bay. A statistical analysis of the data was undertaken at two Aran Island Boundary locations, Aran Bnd West (W) and Aran Bnd South West (SW), which have also been included in Figure 3.1 for reference.

Table 3-1 shows the results of the increase in storminess assessment for the UK Met Office points for the relevant directional sectors. Note sectors marked '-' were not considered relevant directions to the study, and hence were not assessed.

Representative wind speeds were determined with reference to the Offshore Installations: Guidance on design, construction and certification (Reference 3) where appropriate, as per the original 2013 study.



**Figure 3.1: ECMWF and UK Met Office Offshore Wave Data Points**

## PHASE 2 TECHNICAL REPORT

**Table 3-1: Increase in Storminess Assessment – Factors per Directional Sector at UK Met Office Wave Data Points**

UK Met Office Point	0	45	90	135	180	225	270	315
Drogheda	1.12	1	1	1.1	1.3	-	-	-
Bray	1.1	1	1	1.1	1.25	-	-	-
Codling	1.05	1	1	1.1	1.25	-	-	-
Courtown	1	1	1	1.1	1.12	-	-	-
Rosslare	-	-	-	1	-	-	-	-
Dunmore	-	-	-	-	1.1	1.1	-	-

### 3.2 Bathymetric Data

In order to facilitate the transformation of offshore wave conditions into inshore conditions relevant to the assessment of overtopping, detailed inshore bathymetric and topographic information was required to ensure that the transfer of wave energy from offshore to inshore was adequately represented at the specific shoreline or defence line. Sufficient data was also required to represent the various channels, drying zones and offshore banks within the model domain.

The original 2013 study had used the latest bathymetric and topographic data available at the time when establishing the models. A large part of the bathymetry information used in those models was obtained from INFOMAR survey data, a joint project between Geological Survey Ireland (GSI) and the Marine Institute, OPW LiDAR data and significant numbers of more localised hydrographic surveys were also used to provide specific information for inshore areas. Where sufficient inshore information was not available, OPW carried out a number of local topographic surveys in order to establish beach profiles and defence levels. Where data gaps remained, particularly offshore, the above datasets were supplemented with Admiralty Chart data, as digitally supplied by C-Map of Norway.

RPS processed and quality checked all bathymetric data to ensure its suitability for use within the modelling systems, consistently ensuring that any model interpolation processes produced valid meshes which were representative of the input data.

Unlike the Phase 3 detailed assessment areas, for the Phase 2 update, the model bathymetry was not updated, as the existing models were considered sufficient for the purposes of this scale of assessment. This applies to all Phase 2 CAPOs, with the exception of Omeath and Greenore, within Carlingford Lough, and Coonagh within the Shannon Estuary. As the Phase 3 model developed for the Carlingford CAPO was a local estuary model, with the bathymetric data incorporated also relevant to Omeath and Greenore, the same Phase 3 model was used for each CAPO. Likewise, the Phase 3 model developed for the Bunratty CAPO covered the same extents and level of mesh resolution that was required for the Phase 2 Coonagh CAPO.

### 3.3 Water Level Data

The ICWWS 2018 produced updated water levels around the coast of Ireland; refer to the Phase 1 Report for further detail on these water levels and how they were derived (Reference 2). The extreme water levels used to inform the joint probability analysis and wave modelling were therefore taken from the ICPSS / ICWWS 2018 Phase 1 estimation points and covered the full range of required AEPs.

## PHASE 2 TECHNICAL REPORT

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At a number of estimation points, the extreme water levels derived during Phase 1 were marginally lower than the water levels estimated during the ICPSS, but generally within the expected tolerance of the modelling and statistical analysis. As a conservative approach, the final water levels used for the Phase 2 modelling were therefore taken to be the higher of the two sets of results for the majority of AEPs. In a minority of cases, a combination of the two datasets was used, due to the fit of the statistical distribution, whereby the ICWWS 2018 Phase 1 results may have increased for the high frequency events, yet decreased for the low frequency events.

The ICWWS 2018 Phase 1 extreme water levels estimated in the upper Shannon Estuary were notably lower than those of the ICPSS (up to 1 metre), however the significant amount of additional bathymetric and tide gauge data now available, provided improved confidence in the updated levels, which were subsequently adopted for use at the Phase 2 CAPOs, Foynes and Coonagh.

Table 3-2 shows the source of the water level data used within the Phase 2 modelling, and highlights in red any differences above model tolerance (0.15m) between the ICPSS and ICWWS 2018 Phase 1 MSL water levels for the 0.1% AEP event, where relevant.

## PHASE 2 TECHNICAL REPORT

**Table 3-2: Source of Water Level Data for Phase 2 Wave and Water Level Modelling**

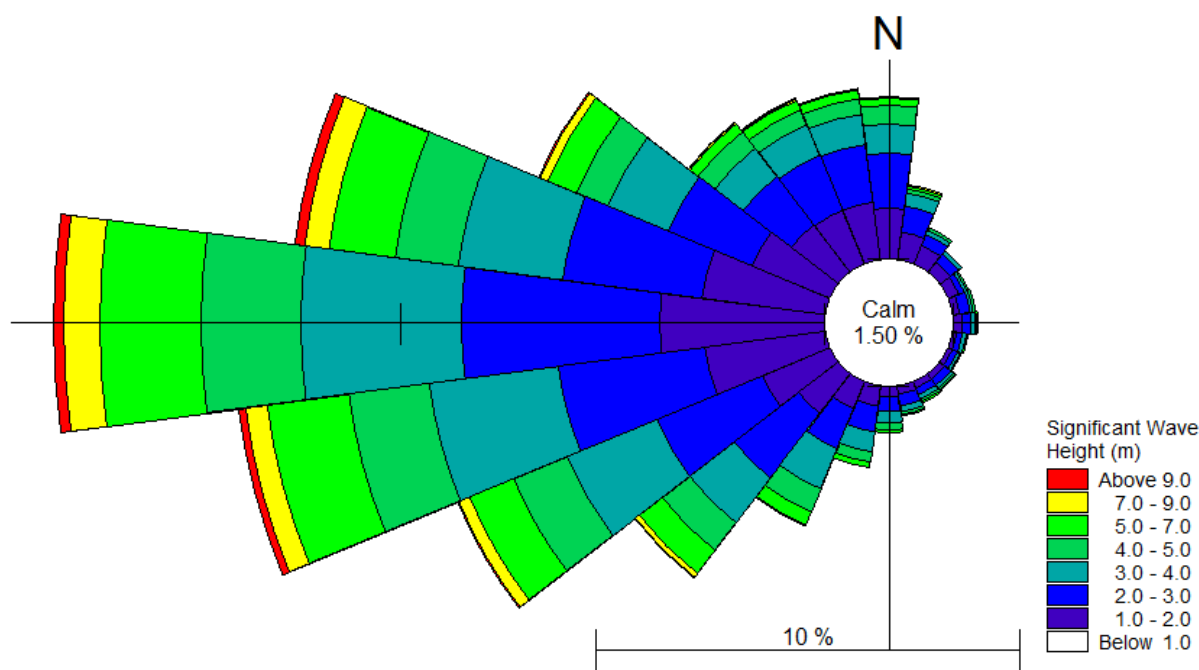
Coastal Area of Potential Overtopping	Water Level Estimation Point	Water Level from ICPSS, ICWWS 2018 Ph1 or Combination	Difference (m) in ICPSS and ICWWS 2018 Ph1 0.1% AEP Water Level
Omeath	NE28	ICWWS2018	-
Greenore	NE28	ICWWS2018	-
Ballynamony	NE1	ICPSS	0.23
Annagassan	NE6	ICPSS	0.23
Dunany	NE6	ICPSS	0.23
Cruisetown	NE9	ICPSS	<0.15
Bettystown	NE9	ICPSS	<0.15
Skerries	NE13	ICPSS	0.23
Malahide	NE17	ICPSS	0.25
Portmarnock	NE17	ICPSS	0.25
Howth	NE17	ICPSS	0.25
Sutton	NE23	ICPSS	0.25
Dublin	NE23	ICPSS	0.25
Bray	SE6	ICPSS/ICWWS 2018	<0.15
Ballydonarea	SE9	ICPSS/ICWWS 2018	<0.15
Blackditch	SE9	ICPSS/ICWWS 2018	<0.15
Wicklow	SE12	ICPSS/ICWWS 2018	<0.15
Arklow	SE17	ICWWS2018	-
Kilbegnet	SE17	ICWWS2018	-
Cahore	SE17	ICWWS2018	-
Wexford	SE33b	ICWWS2018	-
Burrow	SE33b	ICWWS2018	-
Rosslare Strand	SE36	ICWWS2018	-
Arthurstown	W3	ICWWS2018	-
Whitewall	W3	ICWWS2018	-
Dungarvan	S35	ICWWS2018	-
Ardmore	S35	ICWWS2018	-
Cobh	C2 & C4	ICWWS2018	-
Youghal	S35	ICWWS2018	-
Castletownbere	S3	ICPSS	<0.15
Kenmare	SW8	ICPSS	<0.15
Assroe	SW8	ICPSS	<0.15
Waterville	SW12	ICPSS	0.24
Dingle	SW22	ICPSS	0.31
Ballyheige	SW39	ICPSS	<0.15
Tarbert	Sh11	ICPSS	0.2
Foynes	Sh18	ICWWS2018	-
Coonagh	Sh26	ICWWS2018	-
Kilrush	Sh8	ICPSS	0.18
Kilkee	SW51	ICPSS	<0.15
Creggane	SW51	ICPSS	<0.15
Lahinch	SW51	ICPSS	<0.15
Ballyvaghan	SW58	ICWWS2018	-
Dungory	W3	ICPSS	<0.15
Galway	W6	ICWWS2018	-
Spiddle	W9	ICWWS2018	-
Westport	W41	ICPSS	<0.15
Belmullet	W57	ICWWS2018	-
Strandhill	NW6	ICWWS2018	-
Sligo	NW6	ICWWS2018	-
Tullaghan	NW10	ICWWS2018	-
Rosstownlagh	NW12	ICWWS2018	-
Killybegs	NW15	ICWWS2018	-
Dunfanaghy	NW35	ICWWS2018	-
Downings	NW36	ICWWS2018	-
Rathmullan	NW42	ICWWS2018	-
Letterkenny	NW42	ICWWS2018	-
Buncrana	NW42	ICWWS2018	-
Moville	NW52	ICWWS2018	-

‘-’ indicates ICWWS 2018 water levels are higher than ICPSS water levels for the majority of AEPs, and therefore were used within Phase 2



## 4 STATISTICAL ANALYSIS

Offshore wave data from the ECMWF and UK Met Office models was directionally discretised to identify the critical wave directions at offshore locations, relevant to each of the CAPOs. An example of a wind rose showing critical wave directions at an offshore point **55.5°N, 10.0°W**, off the North West coast is shown in Figure 4.1. Wave roses for each of the offshore locations analysed can be found in Appendix A.



**Figure 4.1: Example of Wave Rose on North West Coast at Point 55.5°N, 10.0°W (ECMWF ERA 5 Combined Significant Wave Height)**

Extreme Value Analysis and Joint Probability Analysis of waves and water levels were performed on the offshore data for all CAPOs with the potential to be exposed to offshore storm waves. In the case of CAPOs located within Galway Bay, the analysis was performed on wave data inshore of the Aran Islands, as the presence of these islands and complex bathymetry in the area required a more detailed modelling approach.

In the case of semi enclosed estuaries, such as the Shannon Estuary or locations where the wave climate is driven by local wind-wave generation within the water body rather than being related to the offshore wave climate, the joint probability analysis was undertaken between water levels and wind speeds. In these cases, the relevant combinations of water levels and wind speeds were specified in the setup of the model simulations to allow the computation of the required wave and water level combinations at the shoreline or defence line.

Table 4-1 shows the joint probability variables that were required to be assessed for each CAPO, based on their exposure to offshore waves. Note, in many cases, due to the orientation of parts of the CAPO coastline, both wave transformation modelling from offshore and also local wind wave generation modelling were required.

## PHASE 2 TECHNICAL REPORT

**Table 4-1: Joint Probability Variables required for each CAPO**

Coastal Area of Potential Overtopping	Joint Probability Wave Height & Water Level	Joint Probability Wind Speed & Water Level
Omeath		✓
Greenore		✓
Ballynamony	✓	
Annagassan	✓	
Dunany	✓	
Cruisetown	✓	
Bettystown	✓	
Skerries	✓	✓
Malahide	✓	✓
Portmarnock	✓	✓
Howth	✓	
Sutton	✓	✓
Dublin	✓	
Bray	✓	
Ballydonarea	✓	
Blackditch	✓	
Wicklow	✓	
Arklow	✓	
Kilbegnet	✓	
Cahore	✓	
Wexford		✓
Burrow		✓
Rosslare Strand	✓	
Arthurstown		✓
Whitewall	✓	✓
Dungarvan	✓	✓
Ardmore	✓	
Cobh		✓
Youghal	✓	✓
Castletownbere		✓
Kenmare		✓
Assroe		✓
Waterville	✓	
Dingle		✓
Ballyheige	✓	
Tarbert		✓
Foynes		✓
Coonagh		✓
Kilrush		✓
Kilkee	✓	
Creggane	✓	
Lahinch	✓	
Ballyvaghan	✓	✓
Dungory		✓
Galway	✓	✓
Spiddle	✓	✓
Westport		✓
Belmullet	✓	✓
Strandhill	✓	
Sligo		✓
Tullaghan	✓	
Rossnowlagh	✓	
Killybegs		✓
Dunfanaghy	✓	✓
Downings		✓
Rathmullan		✓
Letterkenny		✓
Buncrana	✓	
Moville		✓

## 4.1 Extreme Value Analysis

Extreme value analysis (EVA) was undertaken by fitting a theoretical probability distribution to the offshore wave heights derived from the ECMWF and UK Met Office data. A partial duration series, also known as peak over threshold model, was used to select the largest events which occurred within the dataset for each relevant directional sector. A Truncated Gumbel probability distribution was fitted to the datasets and using the Jackknife re-sampling technique, a series of return period wave heights for each directional sector was derived.

An equivalent process was applied to the wind data from the same datasets; however in the majority of cases, the derivation of return period wind speed was achieved using the Offshore Installations guidance, in order to ensure consistent wind speeds were achieved.

Results from the EVA are included in Appendix B.

## 4.2 Joint Probability Analysis

The joint probability analysis of wave heights and water levels or wind speeds and water levels was undertaken using the spreadsheet and simplified methodology derived during the JOIN-SEA project, which is described in section 5.7 of the DEFRA/Environment Agency RSD Guidance on Joint Probability Analysis, FD2308 (Reference 4). This methodology involves selecting a correlation coefficient between each pair of variables. Although this is normally based on established relationships (for example wave height and water level) for a particular area, there are no pre-determined correlation coefficients available for the coast of Ireland.

Therefore, as part of the ICWWS 2013, RPS made use of all wind, wave and tide gauge data available at that time, in order to derive joint event matrices between wave heights and water levels, or wind speeds and water levels, to determine an appropriate correlation coefficient for each of the directional sectors, along each section of the study coastline. Due to the limited availability of long term tide gauge data around the coast of Ireland, RPS also made use of previous studies and experience in determining the most suitable correlation coefficients for each case. Correlation coefficients derived as part of the ICWWS 2013 remained the same for the current study, and are discussed further in Section 4.2.1.

Once an appropriate correlation coefficient was selected, the relevant set of AEP water levels and wind speeds or wave heights were input into the JOIN-SEA spreadsheet for analysis. Water levels were taken from the updated ICWWS Phase 1 / ICPSS extreme water level outputs at various estimation points around the coast of Ireland, whilst the wave height data was derived during the EVA stage of this study, as described in Section 4.1. AEP wind speeds were generally calculated using the Offshore Installations guidance (Reference 3).

Six combinations of wave heights and water levels for joint Annual Exceedance Probabilities (AEPs) of 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% were derived for each relevant directional sector at the appropriate offshore locations. Likewise, combinations of wind speeds and water levels were derived for the same AEPs for those CAPOs subject to locally generated wind seas. By deriving six combinations of water levels and wave/wind conditions for every joint AEP, the complete joint probability range was defined for inclusion in the subsequent modelling.

Results from the joint probability analysis are included in Appendix C.

### 4.2.1 Correlation Coefficients

The correlation between wave heights and water levels or wind speeds and water levels varies with storm direction along each section of the coast of Ireland. Thus, the joint probability analysis was undertaken for a range of storm directional sectors. The correlation coefficients derived for each direction along the various coastlines are shown in Table 4-2.

On the north east and south east coasts, there was a strong correlation between the offshore wave heights and water levels for events from the south east and south, with less correlation from the east and the least correlation from the north east.

## PHASE 2 TECHNICAL REPORT

Due to the orientation of the south coast, the derived correlation coefficients were rather different than along the eastern coastline. The analysis indicated that there is a strong correlation between the wave height and water levels for events from the south and south west, with less correlation for events from the south east and east sectors.

On the south west and west coasts, it is the storm events from the west which show the highest correlation, closely followed by the south west. To a lesser degree, the north westerly storms show fair correlation, whilst there is lower correlation for southerly events.

Similarly, on the north west coast, there is high correlation between the offshore wave heights and water levels for events from the west, with medium correlation for the south west and north west. Low correlation was determined for southerly events.

Finally, on the north coast, it is the events from both the west and north west which show the highest correlation between offshore waves and water levels, whilst events from the north and north east show slightly less correlation.

**Table 4-2: Derived Correlation between Offshore Wave Heights and Water Levels**

Direction	Coastline				
	NE/SE	S	SW/W	NW	N
0					0.45
45	0.1				0.35
90	0.25	0.2			
135	0.6	0.28			
180	0.6	0.45	0.25	0.11	
225		0.45	0.45	0.45	
270			0.6	0.6	0.6
315			0.33	0.48	0.6

## 5 MODEL DEVELOPMENT AND SIMULATION

### 5.1 Modelling System

Following the statistical analysis, the derived offshore wave climate / water level pairings for each AEP were transformed to inshore using the MIKE21 Spectral Wave (SW) Flexible Mesh model. The SW model is a third generation spectral wind-wave model with two modes of operation, using either the directional decoupled parametric or fully spectral formulations. For this study, the directional decoupled parametric formulation was used, as it was not necessary to separate out the individual wind and swell components of the waves. The SW module describes the propagation, growth and decay of waves in nearshore areas. The model can take into account the effects of refraction and shoaling due to varying depth, local wind generation and energy dissipation due to bottom friction, white capping and wave breaking. It may also include non-linear wave-wave interaction, wave-current interaction and the effect of time varying water depth and flooding and drying. The SW model has an optimal degree of flexibility in describing bathymetry and ambient flow conditions using depth-adaptive and boundary-fitted unstructured mesh.

### 5.2 Model Bathymetries

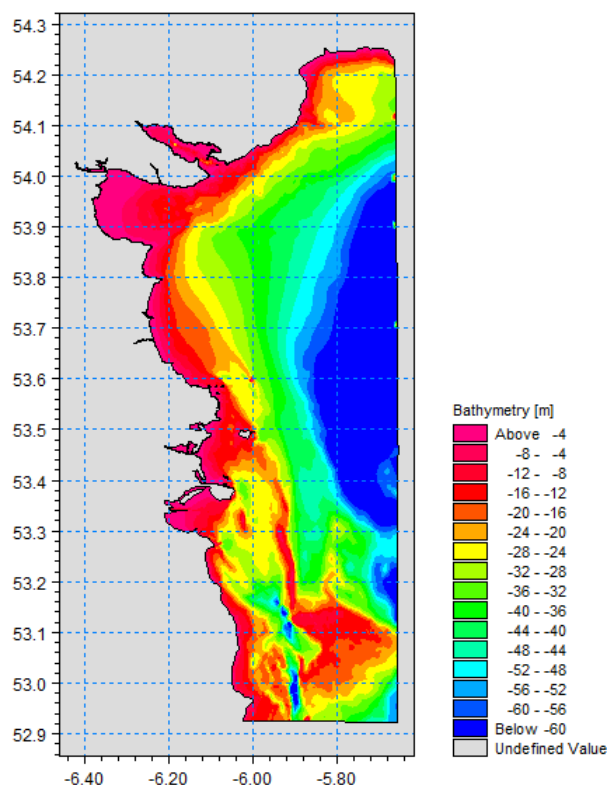
As discussed under Section 3.2, Phase 2 of this study made use of a series of offshore and inshore model bathymetries developed during the original 2013 study. The grid resolution of the models varied depending on location and was selected to ensure that the variation and rate of change in the seabed topography due to banks, rocky shoals and particularly at the approaches to the shorelines / defence lines were adequately resolved so that the changes in wave conditions due to shoaling, refraction and wave breaking were accurately modelled. This required fine grid resolution in places, as low as 10m, particularly around banks and shoals and in the vicinity of the shoreline at all CAPOs, with coarser grid resolution in deeper water and areas of more consistent bathymetry.

Larger offshore base models were used to simulate combined swell and wind waves, with boundaries positioned to accurately represent the wave climate of the ECMWF or UK Met Office data extraction points. Where local wind seas were relevant to the CAPO, the models were more localised but of sufficient extent to simulate the development of wind waves with local fetches. The extents and bathymetries of all base models used in this study are shown in the following figures. These model areas were chosen so as to most efficiently and accurately model all CAPOs and should not be confused with the output study areas, which were based on river basin district extents.

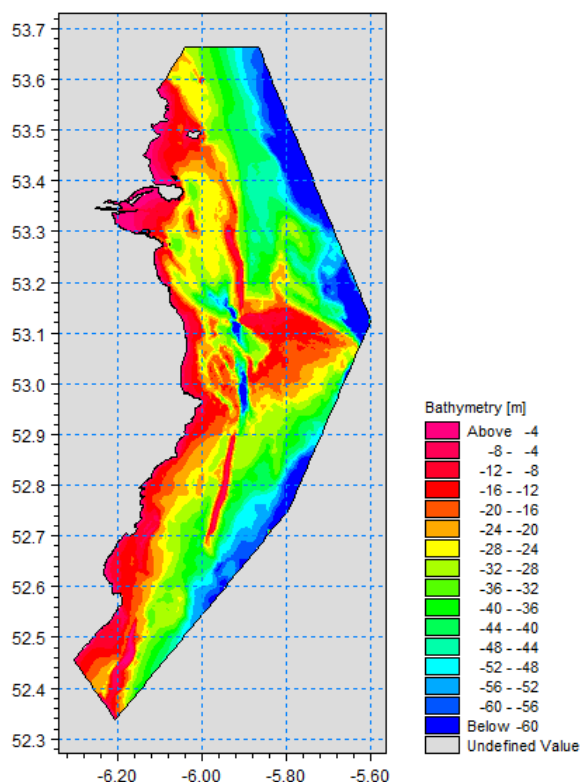
The North East model extends from Ardglass in Northern Ireland to south of Wicklow and was used to simulate combined wave propagation for the Ballynamony, Annagassan, Dunany, Cruisetown, Bettystown, and Howth CAPOs. A local mesh of Carlingford Lough was derived from this base model in order to simulate wind waves for the Omeath and Greenore CAPOs. Both combined waves and local wind waves were simulated for the Skerries, Malahide and Portmarnock CAPOs. Figure 5.1 shows the extent and bathymetry of the North East Coast model.

A second independent model was developed for the south east, extending from north of Skerries to south of Courtown. Combined waves were simulated for the Dublin, Bray, Ballydonarea, Blackditch, Wicklow, Arklow, Kilbegnet and Cahore CAPOs using the South East base model. Due to its positioning, Irish Sea storm waves and locally generated wind waves were run separately for the Sutton CAPO using a derivation of the same mesh. Figure 5.2 provides the bathymetry and extent of the South East Coast model.

## PHASE 2 TECHNICAL REPORT

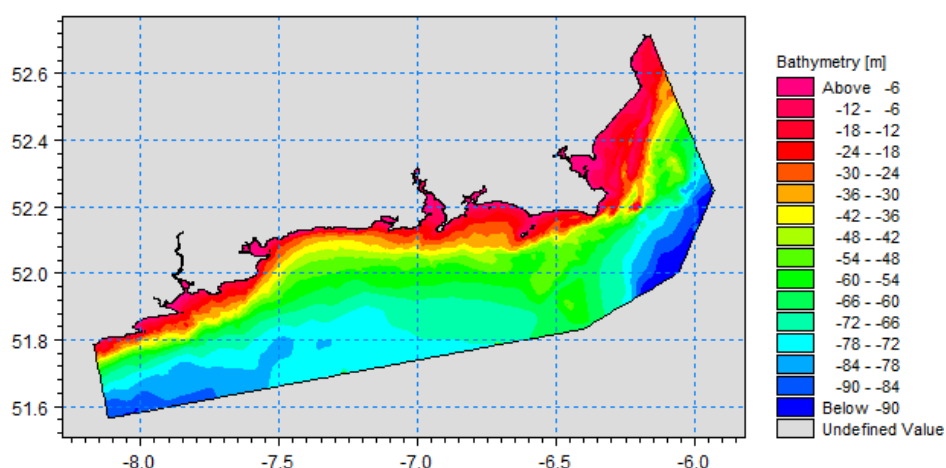


**Figure 5.1: North East Coast Model Extent and Bathymetry (to MSL)**



**Figure 5.2: South East Coast Model Extent and Bathymetry (to MSL)**

The South coast base model (Figure 5.3) extends from north of Courtown to east of Cork and was used to simulate combined waves for the Rosslare Strand and Ardmore CAPOs. The base model was also used to develop local meshes in order to simulate fetch limited wind waves for the Wexford, Burrow and Arthurstown CAPOs. Both combined waves and wind waves were run for the Whitewall and Youghal CAPOs, whilst results for the Dungarvan CAPO were determined by simulating offshore storm waves and locally generated wind waves separately.

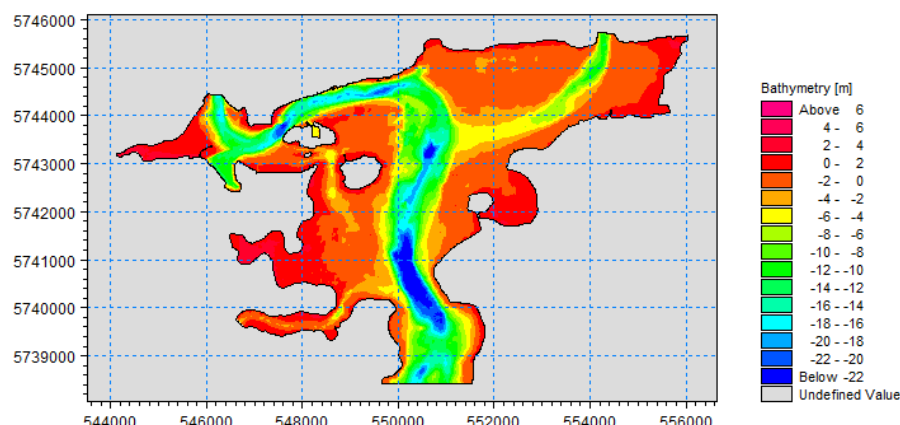


**Figure 5.3: South Coast Model Extent and Bathymetry (to MSL)**

A detailed model of Cork Harbour was prepared in order to simulate the locally generated wind waves in the vicinity of the Cobh CAPO, as shown in Figure 5.4.

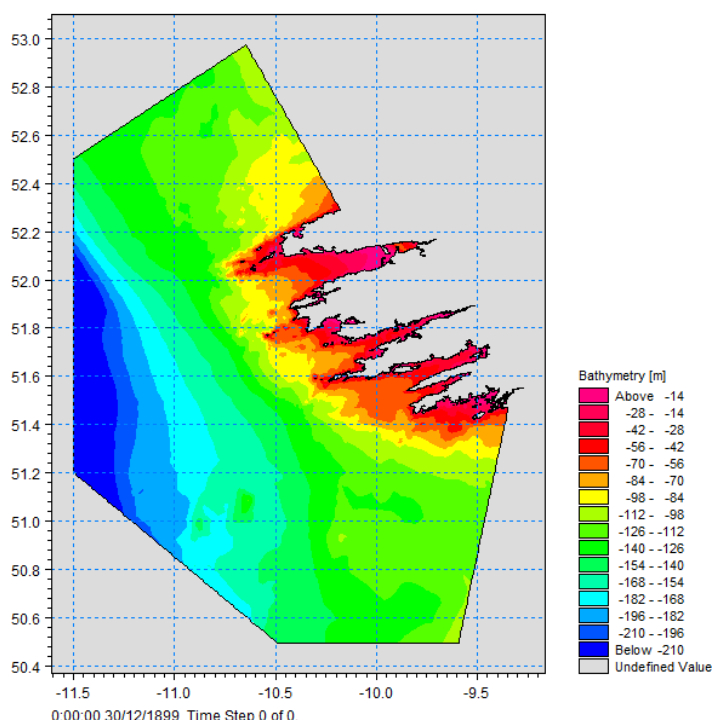


## PHASE 2 TECHNICAL REPORT



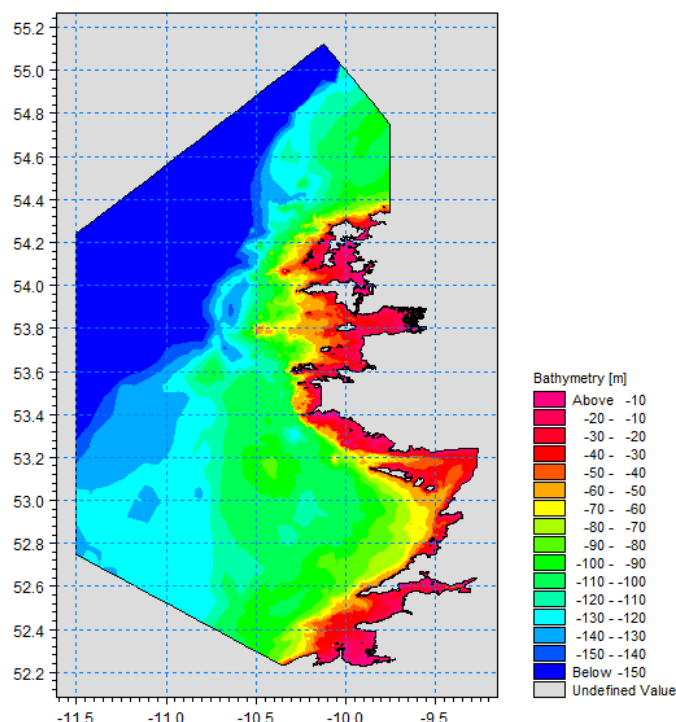
**Figure 5.4: Cork Harbour Model Extent and Bathymetry (to MSL)**

The South West Coast model extended from Baltimore to Tralee and was developed to simulate the propagation of combined waves from offshore to the Waterville coastline, as shown in Figure 5.5. This model was also used as a base model in order to generate a number of local meshes for the Castletownbere, Kenmare, Assroe and Dingle CAPOs, which were used to simulate local wind waves.



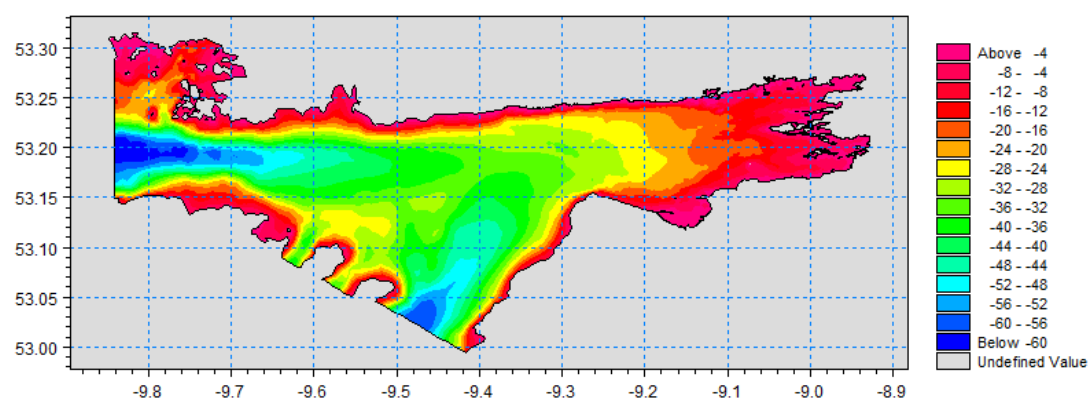
**Figure 5.5: South West Coast Model Extent and Bathymetry (to MSL)**

An expansive base model was developed for the west coast, in order to transform combined waves from offshore to inshore for the Ballyheige, Kilkee, Creggane and Lahinch CAPOs. This model covered the coast from west of Castlegregory to just north of Belmullet. A smaller mesh was derived for Westport which is dominated by local wind waves. Due to the shape of the coastline at Belmullet, both locally generated wind waves and offshore Atlantic storm waves were simulated separately in order to determine the appropriate wave climate at the site. Figure 5.6 shows the extents and bathymetry of the West Coast model.



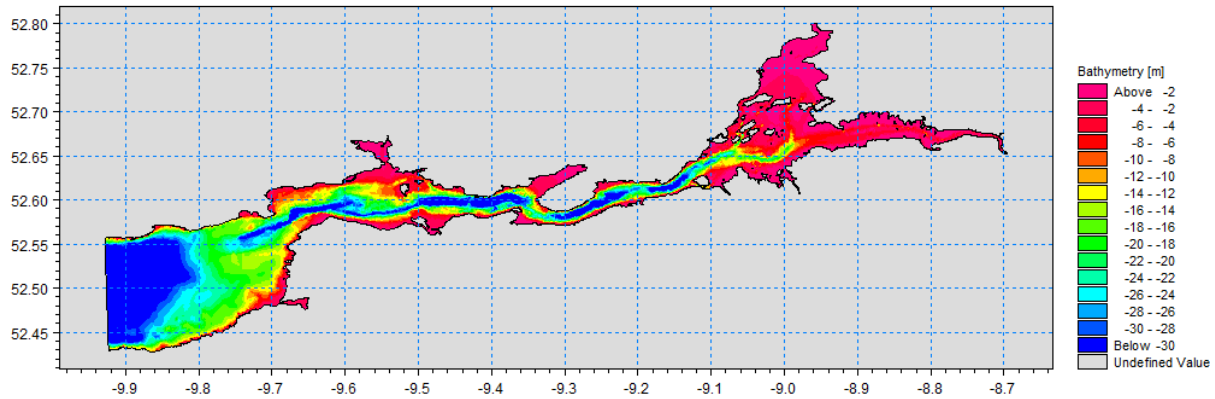
**Figure 5.6: West Coast Model Extent and Bathymetry (to MSL)**

Due to the complex shape of Galway Bay and the presence of the Aran Islands, to reliably simulate the wave climate at the CAPOs located within the bay, it was necessary to use the aforementioned West Coast model to transpose the most recent 15 years of 3 hourly combined wave data offshore to inshore of the Aran Islands. After performing a statistical analysis on the results of this initial transformation, as described in Section 4, the resultant wave climate was transposed from the Aran Islands to the relevant sites, using the model shown in Figure 5.7. Offshore Atlantic storm waves and locally generated wind waves were simulated separately for the Ballyvaghan, Galway and Spiddie CAPOs, with only wind waves required to simulate the wave climate at the Dungory CAPO.



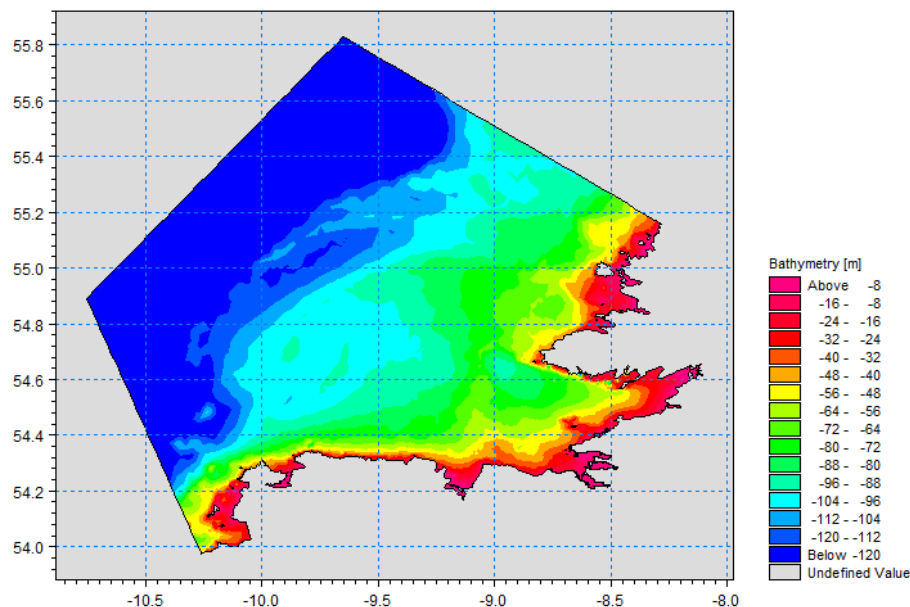
**Figure 5.7: Galway Bay Model Extent and Bathymetry (to MSL)**

A local wind wave model was also developed for the Shannon Estuary, as shown in Figure 5.8 which enabled the simulation of locally generated waves to the Tarbert, Foynes, Kilrush and Coonagh CAPOs.



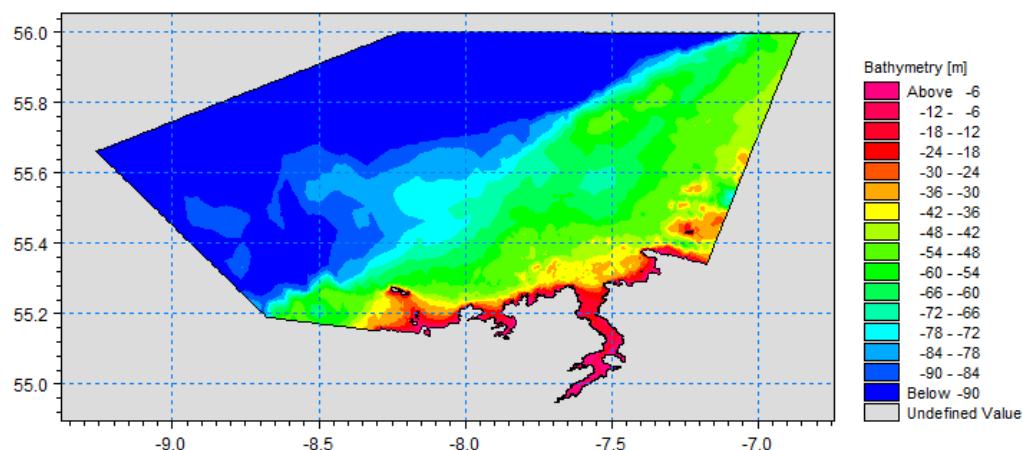
**Figure 5.8: Shannon Estuary Model Extent and Bathymetry (to MSL)**

A North West Coast model extending from Belmullet to Magheraroarty was developed to simulate the combined wave climate at the Strandhill, Tullaghan and Rossnowlagh CAPOs. Using this base model, smaller meshes were also derived in order to generate locally dominant wind waves for the Sligo and Killybegs CAPOs. Figure 5.9 shows the extent and bathymetry of the North West Coast model.



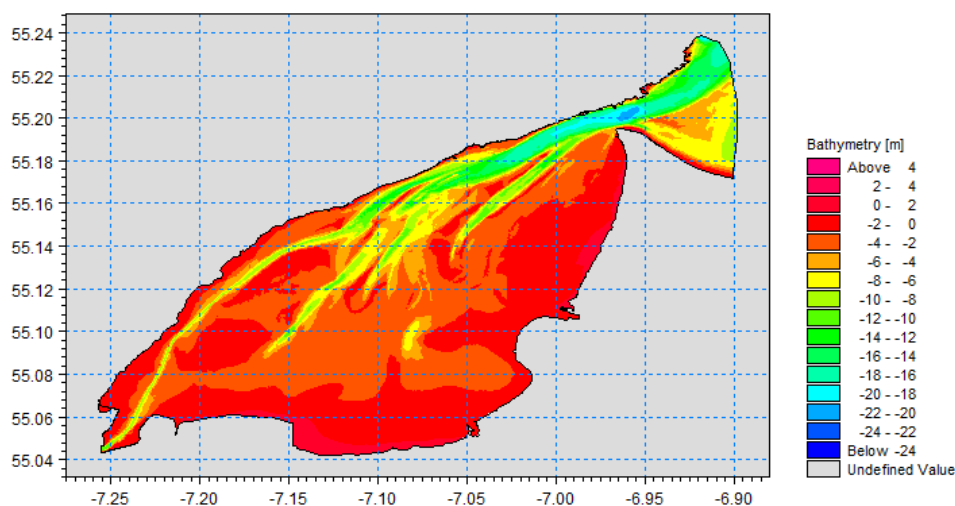
**Figure 5.9: North West Coast Model Extent and Bathymetry (to MSL)**

A further model extending from Magheraroarty to Malin Head was developed in order to simulate the propagation of combined waves from offshore to inshore at Dunfanaghy and Buncrana. Local models of Sheephaven Bay and Lough Swilly were also constructed in order to model the locally generated wind waves for the Downings, Rathmullan and Letterkenny CAPOs. Figure 5.10 shows the model extents and bathymetry for the North Coast model.



**Figure 5.10: North Coast Model Extent and Bathymetry (to MSL)**

Finally, a detailed mesh of Lough Foyle was generated in order to simulate wind waves with local fetches for Moville. Figure 5.11 provides the bathymetry and extents of the Lough Foyle model.



**Figure 5.11: Lough Foyle Model Extent and Bathymetry (to MSL)**

## 5.3 Model Simulations

For those CAPOs potentially exposed to offshore storm wave conditions, the MIKE SW module parametric formulation was used to simulate a series of combined wind and swell waves from offshore to near the shoreline or defence line for a range of exposure directions. The direction which resulted in the most arduous conditions along a particular section of coastline was used to define the inshore wave climate which is provided as the output from this study. It should be noted that for a particular CAPO, the critical storm direction often changed along the coast, resulting in the need to output data at a number of estimation locations for some CAPOs with more complex coastlines.

A similar approach was applied to those locations dominated by locally generated wind waves, with the critical directions assessed in order to establish the most onerous wave climate for each stretch of coastline within the CAPO. Where wind waves were dominant but offshore storm (or swell) waves could still reach the site under similar storm event conditions, both offshore storm waves and locally generated wind waves were transformed separately in order to provide a more comprehensive assessment as the longer period and greater energy of the offshore storm waves have a greater effect on overtopping. Where, simulations indicated significant offshore storm waves could not reach the CAPO, the local wind wave climate is provided as the worst case overtopping scenario and resultant output. Thus by evaluating all possible wave climate scenarios,

## PHASE 2 TECHNICAL REPORT

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the assessment methodology ensured that the most onerous wave conditions were identified for each AEP event at the relevant part of the coast.

Final simulations were undertaken for six combinations of wind speeds and water levels for joint AEP events of 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% for each critical direction. The critical directions for the combined wave, wind wave and swell wave simulations undertaken for each CAPO are listed in Table 5-1.

## PHASE 2 TECHNICAL REPORT

**Table 5-1: Critical Directions simulated for Combined, Swell and Wind waves for each CAPO**

Coastal Area of Potential Overtopping	Critical Directions simulated for Combined Waves (°)	Critical Directions simulated for Swell Waves (°)	Critical Directions simulated for Wind Waves (°)
Omeath			330, 340
Greenore			330, 340
Ballynamony	75, 120		
Annagassan	75, 90		
Dunany	75, 90		
Cruisetown	135		
Bettystown	135		
Skerries	120		310
Malahide	45, 75, 120		10, 350
Portmarnock	45, 75, 120		10, 350
Howth	45, 75, 120		
Sutton	120, 150	150	190, 210
Dublin	120, 150		
Bray	120		
Ballydonarea	120		
Blackditch	120		
Wicklow	45, 120		
Arklow	120, 165		
Kilbegnet	120, 165		
Cahore	120, 165		
Wexford			40, 340, 280
Burrow			40, 340, 280
Rosslare Strand	120		
Arthurstown			200, 310
Whitewall	165		200, 310
Dungarvan	165	165	10, 140, 170, 200, 270
Ardmore	165		
Cobh			110, 140, 170
Youghal	165		10, 140, 170, 200, 270
Castletownbere			200
Kenmare			140, 200, 230, 240
Assroe			140, 200, 230, 240
Waterville	230		
Dingle			140, 150, 200
Ballyheige	280		
Tarbert			110, 280
Foynes			30, 300, 310, 340
Coonagh			50, 260, 280
Kilrush			200, 230, 260
Kilkee	260, 280		
Creggane	260, 280		
Lahinch	260, 280		
Ballyvaghan	270		0, 310, 340
Dungory			0, 300
Galway	270		140, 180, 200, 230
Spiddle	270		190, 230, 240
Westport			260, 270, 280, 290, 300
Belmullet	225		140, 170, 200, 230
Strandhill	260		
Sligo			260, 280, 315
Tullaghan	285		
Rossnowlagh	270		
Killybegs			50, 140, 200
Dunfanaghy	30		20
Downings			230
Rathmullan			200
Letterkenny			30, 50
Buncrana	300, 315		
Moville			200



## 6 IMPACT OF SEA LEVEL RISE

Even without considering any increase in offshore wave heights due to the effect of climate change, the predicted increase in sea levels due to global warming has the potential to increase the wave climate at the shoreline/defence line due to greater water depths being available in the nearshore area. At present there is uncertainty about how global warming will actually affect the offshore wave climate or wind conditions in the future, together with sea levels, thus the assessment of the effects of climate change in this study has considered four sea level rise scenarios.

For the purposes of flood risk assessment the current standard future scenario values adopted in Ireland for sea level rise are 0.5m for the Mid Range Future Scenario (MRFS) and 1.0m for the High End Future Scenario (HEFS), and thus these values were adopted for this study. Two additional climate change scenarios corresponding to sea level rise of 1.5m (H+EFS) and 2.0m (H++EFS) were also included. Each of these future scenarios are shown in Table 6-1.

**Table 6-1: Sea Level Rise for various Future Scenarios**

Future Scenario	Sea Level Rise from Present Day
Mid Range Future Scenario (MRFS)	0.5m
High End Future Scenario (HEFS)	1.0m
High+ End Future Scenario (H+EFS)	1.5m
High++ End Future Scenario (H++EFS)	2.0m

Wave modelling scenarios undertaken for the present day were re-run for these four climate change scenarios. The simulations were undertaken for the wave directions which were established as the critical directions for each section of the coastline during the present day simulations but with the water level increased by the relevant amount.

## 7 MEAN SEA LEVEL TO OD MALIN CONVERSION

A review of the Mean Sea Level (MSL) to OD Malin datum relationship around the coast of Ireland was undertaken as part of Phase 4 of the ICWWS 2018 (Reference 5). The aim of Phase 4 was to assess and estimate the height difference relationship between Mean Sea Level (MSL) and Ordnance Datum (OD) Malin (OSGM15 and OSGM02) at relevant gauged and non-gauged locations around the coast of Ireland.

Harmonic Analysis was undertaken on each suitable gauge using the Danish Hydraulic Institute (DHI) – MIKE 21 toolbox ‘Tidal Analysis of Heights’. Due to sea level rise and other factors, the MSL to OD Malin relationship is constantly changing, therefore an approach which incorporated sensitivity testing was adopted. Hence, where the length of record and quality of the data was suitable, each gauge dataset was analysed a number of times, for different periods of record.

Once the best estimate of the relationship between MSL and OD Malin (OSGM15) was determined at each suitable gauge, a range of surface datasets were investigated and manipulated to develop a corrective surface whereby the MSL to OD Malin (OSGM15) and OD Malin (OSGM02) relationships could be applied at non-gauged locations. These gridded corrective surface datasets were used to provide the conversions from MSL to OD Malin (OSGM15) and OD Malin (OSGM02) for the output water level data at each of the CAPO estimation locations considered in this Phase 2 study.

## 8 RESULTS AND STUDY OUTPUT

The North East, South East and South Coast models were generally subject to waves approaching from the north east through east to south directions. Offshore boundary conditions for these models included north easterly waves of up to 8 metres significant height and 12.5 seconds peak period for the 0.1% AEP event, and significant heights of up to 8 and 10.5 metres, with peak periods of circa 12.5 and 14 seconds from the east and south easterly directions respectively. For the southerly direction, offshore waves were up to 14 metres significant height and 16.5 seconds peak period.

In contrast to the North East, South East and South Coast models, the South West and West Coast models focussed on waves approaching from the south westerly and westerly directions. Offshore wave boundary conditions ranged from circa 17 to 21 metres significant height and 20 and 23 seconds peak period for the south west and west directions respectively for the 0.1% joint AEP event.

Boundary conditions for the North West Coast model included offshore waves in the order of 17 metres significant height and 20 seconds peak period from the south west and north westerly directions, with larger waves from the west of up to 21.5 metres significant height and 23 seconds peak period. The offshore boundary conditions for the North Coast model included north-westerly waves in the order of 18.5 metres significant height and 21 seconds peak period. Smaller wave heights of circa 13 metres, with peak periods of up to 18 seconds were applied to the offshore boundaries of the North Coast model to represent waves approaching from the north and north easterly directions.

All of the models were run for the full range of water level and wave height combinations for each joint probability event up to the 0.1% AEP, i.e. six combinations of wave conditions and water levels for each event for the appropriate directional sectors. Once these waves were transformed from offshore to inshore, or similarly when inshore waves were generated by local wind conditions in fetch limited scenarios, the inshore results were extracted.

For each of the AEP events from 50% to 0.1%, the output of the study near the shoreline / defence line at each CAPO, is presented in terms of spectral significant wave height ( $H_{m0}$ ) in metres, spectral peak wave period ( $T_p$ ) in seconds and mean wave direction (MWD) in degrees measured from north, for each water level (WL).

Due to the effects of refraction, the storm wave direction at the shoreline was normally within  $\pm 30^\circ$  of the direction normal to the coastline, apart from in areas with complex nearshore bathymetry such as Westport. Thus while the wave direction at the shoreline/defence line is therefore generally not critical for overtopping calculations, the mean wave direction of the inshore wave conditions has been provided for completeness, for all locations.

Wave climate is generally referred to in terms of combined waves or wind waves. When a particular stretch of coastline has the potential to be affected by both offshore storm waves and locally generated wind waves under similar storm conditions but from different directions, each component is provided separately and termed swell waves and wind waves.

For this study the output wave conditions are representative of a location situated at approximately half the shallow water wavelength seaward from the toe of the defence structure or shoreline. For shorter period waves this may be in the order of circa 10 metres, increasing with distance for larger swell or combined waves. A note of the measured or assumed bed level and its source is also supplied.

Wave climate and water level combinations are provided for present day sea levels and for each of four sea level rise scenarios (MRFS, HEFS, H+EFS and H++EFS).

For clarity, a sample results table for the present day conditions at Wicklow is shown in Table 8-1, with the position of the estimation locations shown in Figure 8.1. There are two estimation locations provided for this CAPO; Location A which is exposed to combined waves from the east and Location B which is more sheltered due to its position inside the harbour, and consequently is exposed to combined waves from the north east. Combined waves are inclusive of both the wind wave and swell wave elements.

Maximum significant wave heights at Location A range from 2.45 metres to 3.05 metres for the 50% and 0.1% AEP events respectively, with corresponding peak wave periods of 8.56 and 10.59 seconds. Location B is

## PHASE 2 TECHNICAL REPORT

subjected to smaller wave heights with shorter periods, ranging from a maximum significant height of 1.56 metres with a corresponding peak period of 7.25 seconds for the 50% AEP event to 2.02 metres significant height and 8.77 seconds peak period for the 0.1% AEP event.

Water levels ranged from 1.14 metres OD Malin (OSGM15) to 2.35 metres OD Malin (OSGM15) for a 0.1% AEP event. Bed levels at which the output data was extracted are -2.22 metres and -2.49 metres OD Malin (OSGM15) for Locations A and B, respectively.

**Table 8-1: Sample Output for Wicklow**

Location A						
Present Day Scenario Water Level						
AEP	Water Level (m)			Comb Wave Component		
	MSL	OD Malin OSGM02	OD Malin OSGM15	Hm0 (m)	Tp (s)	MWD (°)
50%	1.35	1.32	1.32	2.45	8.56	79
	1.44	1.41	1.41	2.38	8.28	80
	1.52	1.49	1.49	2.21	7.85	81
	1.63	1.60	1.60	1.83	7.13	83
	1.71	1.68	1.68	1.47	6.50	85
	1.79	1.76	1.76	1.06	5.69	88
20%	1.35	1.32	1.32	2.56	9.05	78
	1.52	1.49	1.49	2.52	8.67	79
	1.63	1.60	1.60	2.36	8.13	80
	1.71	1.68	1.68	2.13	7.67	82
	1.79	1.76	1.76	1.81	7.13	83
	1.90	1.87	1.87	1.30	6.21	87
10%	1.44	1.41	1.41	2.65	9.43	78
	1.63	1.60	1.60	2.57	8.72	79
	1.71	1.68	1.68	2.46	8.34	80
	1.79	1.76	1.76	2.25	7.87	82
	1.90	1.87	1.87	1.85	7.19	84
	1.99	1.96	1.96	1.48	6.55	86
5%	1.44	1.41	1.41	2.69	9.76	78
	1.63	1.60	1.60	2.70	9.27	79
	1.79	1.76	1.76	2.55	8.53	80
	1.90	1.87	1.87	2.30	7.96	82
	1.99	1.96	1.96	2.01	7.43	83
	2.08	2.05	2.05	1.65	6.86	85
2%	1.52	1.49	1.49	2.78	10.20	78
	1.71	1.68	1.68	2.79	9.57	79
	1.90	1.87	1.87	2.67	8.78	80
	1.99	1.96	1.96	2.53	8.38	81
	2.08	2.05	2.05	2.30	7.94	82
	2.19	2.16	2.16	1.87	7.22	85
1%	1.52	1.49	1.49	2.81	10.52	78
	1.71	1.68	1.68	2.85	10.05	78
	1.90	1.87	1.87	2.82	9.32	79
	2.08	2.05	2.05	2.63	8.56	81
	2.19	2.16	2.16	2.34	8.00	82
	2.29	2.26	2.26	2.03	7.50	84
0.5%	1.52	1.49	1.49	2.84	10.81	78
	1.71	1.68	1.68	2.91	10.57	78
	1.90	1.87	1.87	2.91	9.81	79
	2.08	2.05	2.05	2.84	9.16	80
	2.29	2.26	2.26	2.47	8.23	82
	2.38	2.35	2.35	2.18	7.74	83
0.1%	1.63	1.60	1.60	2.95	11.49	78
	1.79	1.76	1.76	3.01	11.28	78
	1.99	1.96	1.96	3.05	10.59	79
	2.19	2.16	2.16	3.04	9.85	79
	2.29	2.26	2.26	3.02	9.57	79
	2.38	2.35	2.35	2.94	9.21	80

Location B						
Present Day Scenario Water Level						
AEP	Water Level (m)			Comb Wave Component		
	MSL	OD Malin OSGM02	OD Malin OSGM15	Hm0 (m)	Tp (s)	MWD (°)
50%	1.17	1.14	1.14	1.56	7.25	46
	1.25	1.22	1.22	1.43	7.27	46
	1.30	1.27	1.27	1.24	6.99	46
	1.35	1.32	1.32	1.13	6.80	45
	1.44	1.41	1.41	0.86	6.34	45
	1.52	1.49	1.49	0.55	5.40	45
20%	1.17	1.14	1.14	1.75	7.62	46
	1.25	1.22	1.22	1.66	7.65	46
	1.35	1.32	1.32	1.40	7.30	46
	1.44	1.41	1.41	1.22	7.01	45
	1.52	1.49	1.49	0.97	6.58	45
	1.63	1.60	1.60	0.55	5.48	45
10%	1.17	1.14	1.14	1.83	7.87	46
	1.35	1.32	1.32	1.55	7.53	46
	1.44	1.41	1.41	1.45	7.35	46
	1.52	1.49	1.49	1.21	7.00	45
	1.63	1.60	1.60	0.84	6.27	45
	1.71	1.68	1.68	0.55	5.41	45
5%	1.17	1.14	1.14	1.87	8.11	46
	1.35	1.32	1.32	1.72	7.80	46
	1.52	1.49	1.49	1.38	7.29	46
	1.63	1.60	1.60	1.10	6.82	46
	1.71	1.68	1.68	0.89	6.41	45
	1.79	1.76	1.76	0.57	5.51	45
2%	1.17	1.14	1.14	1.91	8.46	47
	1.35	1.32	1.32	1.86	8.17	46
	1.52	1.49	1.49	1.64	7.68	46
	1.63	1.60	1.60	1.41	7.33	46
	1.71	1.68	1.68	1.24	7.06	45
	1.79	1.76	1.76	0.98	6.60	45
1%	1.17	1.14	1.14	1.93	8.61	47
	1.35	1.32	1.32	1.92	8.40	46
	1.52	1.49	1.49	1.79	7.98	46
	1.71	1.68	1.68	1.38	7.29	46
	1.79	1.76	1.76	1.23	7.04	46
	1.90	1.87	1.87	0.87	6.39	45
0.5%	1.17	1.14	1.14	1.94	8.84	47
	1.35	1.32	1.32	1.96	8.57	47
	1.52	1.49	1.49	1.90	8.22	46
	1.71	1.68	1.68	1.59	7.56	46
	1.90	1.87	1.87	1.09	6.85	46
	1.99	1.96	1.96	0.92	6.49	45
0.1%	1.17	1.14	1.14	1.95	9.28	47
	1.35	1.32	1.32	2.00	9.14	47
	1.52	1.49	1.49	2.02	8.77	47
	1.71	1.68	1.68	1.94	8.27	46
	1.90	1.87	1.87	1.61	7.69	46
	2.08	2.05	2.05	1.19	7.05	46



**Figure 8.1: Sample Estimation Location Plot for Wicklow**

The complete set of results from the modelling simulations, grouped by study area, can be found in Appendices D to J. Location plots are included in order to show the sections of coastline to which the results tables refer. Table 8-2 shows the relevant Appendix for each study area.

**Table 8-2: List of Appendices by Study Area**

<b>Appendix</b>	<b>Study Area</b>
D	East
E	South East
F	Cork Harbour
G	South West
H	West
I	Shannon Estuary
J	North West Neagh Bann

## 9 REFERENCES

**Reference 1:** RPS, November 2013, Technical Report, "Irish Coastal Wave & Water Level Modelling Study – Coastal Areas Potentially Vulnerable to Wave Overtopping"

**Reference 2:** RPS, September 2020, "Irish Coastal Wave and Water Level Modelling Study 2018 – Phase 1 – Extreme Water Levels"

**Reference 3:** Department of Energy, January 1990, "Offshore Installations: Guidance on design, construction and certification, Fourth Edition, Section 11, Environmental considerations"

**Reference 4:** DEFRA / Environment Agency, March 2005, R&D Technical Report FD2308/TR2, "Use of Joint Probability Methods in Flood Management: A Guide to Best Practice"

**Reference 5:** RPS, November 2020, "Irish Coastal Wave and Water Level Modelling Study 2018 – Phase 4 – Review of Mean Sea Level and OD Malin Relationship for the Coast of Ireland"



## 10 GLOSSARY OF TERMS

<b>Admiralty Chart data</b>	Bathymetry data extracted via C-Map representing Admiralty Charts produced by the United Kingdom Hydrographic Office.
<b>AEP</b>	AEP denotes Annual Exceedance Probability. This is the probability of an event occurring or being exceeded in any one year. For example a 0.5% AEP event has a 0.5% probability (or 1 in 200 chance) of occurring or being exceeded in any one year. Similarly, a 0.1% AEP event has a 0.1% probability (or 1 in 1000 chance) of occurring or being exceeded in any one year.
<b>Astronomic tides</b>	Daily change in sea water levels due to the rotation of the earth and the gravitational forces of the sun and moon along with the hydrodynamic response to the bathymetry.
<b>Bathymetry</b>	Data giving the depth of a large water body to provide the underwater topography.
<b>CAPO</b>	Coastal Area Potentially Vulnerable to Wave Overtopping.
<b>CFRAM</b>	Catchment Flood Risk Assessment and Management.
<b>C-Map</b>	Part of the MIKE Suite of Software, enabling bathymetry data to be extracted for modelling purposes.
<b>Correlation Coefficients</b>	The measure of interdependence of two or more variables that range in value from a positive or negative number. A correlation coefficient of 0 indicates no relationship whereby +/-1 indicates a perfect positive/negative relationship.
<b>Datum</b>	An imaginary surface or set of points used to define the size and shape of a geoid on the earth's surface and the base point from which heights and depths of all other points on the earth's surface are measured.
<b>DEFRA</b>	Department for Environment, Food and Rural Affairs.
<b>DHI</b>	Danish Hydraulic Institute – developer of MIKE modelling software
<b>Directional Decoupled Parametric</b>	Formulation based on parameterisation of the wave action conservation equation.

<b>ECMWF</b>	European Centre for Medium Range Weather Forecasts: International meteorological organisation funded by large number of European national meteorological services.
<b>ERA 5</b>	Created by ECMWF, the ERA 5 dataset contains a large amount of reanalysis climate data for years 1950-present.
<b>European and UK Waters Wave Model</b>	UK Met Office wave model covering UK and European waters, of higher spatial resolution than the global model.
<b>EVA</b>	Extreme Value Analysis: A statistical analysis of stochastic processes to estimate the probabilities of rare or extreme events.
<b>Fetch</b>	The sea surface distance over which wave generating winds blow.
<b>Fully Spectral</b>	Formulation based on the wave action conservation equation, where the directional-frequency wave action spectrum is the dependent variable.
<b>GSI</b>	Geological Survey Ireland: provide information and data on aspects of Irish geology.
<b>Harmonic Analysis</b>	The assessment of a tidal record to describe the tidal variation by harmonic constituents.
<b>HEFS</b>	High End Future Scenario; an addition of 1.0m to the present day estimated extreme sea levels.
<b>H+EFS</b>	High+ End Future Scenario; an addition of 1.5m to the present day estimated extreme sea levels.
<b>H++EFS</b>	High++ End Future Scenario; an addition of 2.0m to the present day estimated extreme sea levels.
<b>ICPSS</b>	Irish Coastal Protection Strategy Study.
<b>ICWWS 2013</b>	Irish Coastal Wave and Water Level Modelling Study – <i>Original Study</i> .

## PHASE 2 TECHNICAL REPORT

<b>ICWWS 2018</b>	Irish Coastal Wave and Water Level Modelling Study 2018 – <i>Current Study</i> .
<b>INFOMAR</b>	Surveying programme managed by GSI and Marine Institute with the aim of surveying and mapping most of the offshore Irish seabed.
<b>Jack-knife Resampling Technique</b>	A method for establishing the uncertainty of a particular probability distribution in relation to a data set. In the jackknife resampling method the bias and the standard deviation of the quantile estimate is calculated by sampling $n$ data sets of $(n-1)$ elements from the original data set.
<b>JOIN-SEA</b>	Specialist joint probability software developed as part of a DEFRA / Environment Agency Project.
<b>Joint Probability Analysis</b>	Analysis to derive the probability of occurrence of events in which two or more specific outcomes will simultaneously occur.
<b>LiDAR data</b>	Light Detection and Ranging: Uses light signals through lasers and optical detectors to measure land elevation.
<b>M2 Buoy</b>	Irish Sea weather buoy managed by the Marine Institute, Met Éireann and the UK Met Office.
<b>Marine Institute</b>	Coordinates marine research and development in Ireland, including the management of a system of tide gauges around the coastline.
<b>Mean Wave Direction (MWD)</b>	The mean of the individual wave directions in the spectrum, measured from North.
<b>MRFS</b>	Mid-Range Future Scenario; an addition of 0.5m to the present day estimated extreme sea levels.
<b>MIKE Spectral Wave (SW) Flexible Mesh module</b>	Two dimensional flexible mesh wave modelling package produced by DHI (The Danish Hydraulic Institute)
<b>MSL</b>	Mean Sea Level: the average sea surface level of all tides over a long period of time.
<b>O.D. Malin</b>	Ordnance Datum Malin: A vertical land levelling datum currently used in the Republic of Ireland based on the mean sea level recorded between January 1960 and December 1969 measured at Malin Head tide gauge.

## PHASE 2 TECHNICAL REPORT

<b>OPW</b>	Office of Public Works.
<b>OSGM02</b>	Outdated transformation model produced by the Ordnance Surveys of Great Britain (OS), Ireland (OSi) and Land & Property Services – Used to link the national height reference system of Ireland (O.D. Malin) with measurements using GNSS.
<b>OSGM15</b>	Updated transformation model produced by the Ordnance Surveys of Great Britain (OS), Ireland (OSi) and Land & Property Services – Used to link the national height reference system of Ireland (O.D. Malin) with measurements using GNSS.
<b>OSi</b>	Ordnance Survey Ireland is the National Mapping Agency for Republic of Ireland.
<b>Overtopping</b>	The flow of water due to wave action, over the crest of a coastal structure or natural defence.
<b>Present day sea levels</b>	Estimated extreme sea levels relative to the current existing scenario, based on the data available at the time of the study.
<b>Refraction</b>	The change in direction of a wave due to propagation over different water depths.
<b>Seich</b>	Abrupt changes in meteorological conditions, such as the passage of an intense depression, may cause oscillations in sea level (or Seiches). The period between these successive waves may vary between a few minutes and around two hours. Small seiches are not uncommon around the coast of Ireland.
<b>Shoaling</b>	The effect when waves propagate from deeper water to more shallow depths, whereby wave height is increased, due to a reduction in the group velocity.
<b>Spectral Peak Wave Period / <math>T_p</math></b>	Representative of the most energetic wave in the wave spectrum.
<b>Spectral Significant Wave Height / <math>H_{m0}</math></b>	Representative of the mean of the highest third of the waves in a wave spectrum.
<b>Surge</b>	An increase (or decrease if negative) in tidal flow or elevation compared to the expected flow or elevation due to astronomic tides. Surge can be caused by high winds (storm surge) and / or atmospheric pressure.
<b>Surge Residual</b>	The change in sea level caused by the effect of pressure variations and persistently strong winds.

## PHASE 2 TECHNICAL REPORT

<b>Swell waves</b>	Waves generated by offshore weather systems.
<b>Theoretical Probability Distributions</b>	A statistical function that describes all possible values and likelihoods that a random variable can take within a given range.
<b>Tidal Analysis of Heights</b>	Part of the MIKE 21 toolbox by DHI, which involves the assessment of a tidal record to describe the tidal variation by harmonic constituents
<b>Tolerance</b>	An interval of confidence for a particular dataset.
<b>Topographic</b>	Data describing the changes in surface elevation in relation to a fixed datum.
<b>Truncated Gumbel probability distribution</b>	A probability distribution whereby the random variable follows the Gumbel distribution truncated at the threshold value from the Peak Over Threshold (POT) analysis.
<b>UK Met Office</b>	National meteorological service for the United Kingdom.
<b>Wave breaking</b>	When the crest of the wave overturns due to the ratio of wave height and water depth.
<b>Wave Set-up</b>	An increase in water level as a consequence of the radiation stresses produced by wave action.
<b>WAVEWATCH III</b>	Third generation global wave model developed at NOAA / NCEP.
<b>Wind Waves</b>	Waves generated by the immediate local wind.