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IRISH COASTAL WAVE AND WATER LEVEL MODELLING STUDY 2018

Phase 1 – Extreme Water Levels



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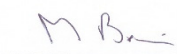
PHASE 1 TECHNICAL REPORT

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EXECUTIVE SUMMARY

This report presents the work undertaken and the findings of Phase 1 of the Irish Coastal Wave and Water Level Modelling Study (ICWWS) 2018. Phase 1 provides an update to the Extreme Coastal Water Levels for the coast of Ireland, originally presented as output from the Irish Coastal Protection Strategy Study (ICPSS) undertaken between 2004 and 2013, which estimated water levels for a range of Annual Exceedance Probability (AEP) events at a series of points around the coast of Ireland.

The assessment areas adopted for Phase 1 of the ICWWS 2018 align with those employed in the ICPSS and are listed below.

- **North East Coast** – Omeath to Dalkey Island
- **South East Coast** – Dalkey Island to Carnsore Point
- **South Coast** – Carnsore Point to Bantry Bay
- **South West Coast** – Bantry Bay to Ballyvaghan Bay
- **West Coast** – Ballyvaghan Bay to Killala Bay
- **North West Coast** – Killala Bay to Lough Foyle

The knowledge of extreme water levels around the coast is a key element in the assessment of risk associated with coastal flooding and coastal change and the development of associated management strategies. It also allows informed decisions to be made on related coastal risk management schemes and provides the information to inform the design of such schemes. These extreme water levels are also critical for estimating and modelling the potential wave climate at the shoreline, as assessed under Phases 2 and 3 of this study, and for providing the joint probability information required to undertake wave overtopping, flood and other risk assessments, where relevant.

A combination of analytical and numerical modelling techniques, developed and proven capable of estimating extreme tidal levels of various Annual Exceedance Probabilities (AEP) to the required accuracy in the ICPSS pilot study (Reference 1) were applied for this study. At many of the estimation points on the North West, West, South and South East coasts, this study produced an uplift in the extreme water levels (relative to mean sea level datum, MSL), compared to those derived during the ICPSS. In other cases, a reduction in levels was indicated, particularly along the North East and South West coasts, however the differences were generally noted to be within the tolerance of the modelling and analytical processes. When a comparison was made between the ICWWS 2018 and ICPSS water levels to OD Malin (OSGM02), an increase in extreme water levels was evident at the majority of estimation points. One area, the upper Shannon Estuary, showed a notable decrease in water levels between the ICPSS and the ICWWS 2018, however at the time of the ICPSS assessments, there was limited bathymetric and gauge data available in this area, and the results to the east of the Fergus Estuary were deemed to be unreliable. Due to recent acquisition of LiDAR data in the Fergus Estuary (2012) and the installation of several tide gauges over the intervening period to provide data for validation, the accuracy and confidence in the ICWWS 2018 modelling in the Shannon Estuary has improved significantly.

1 INTRODUCTION

This report presents the work undertaken and the findings of Phase 1 of the Irish Coastal Wave and Water Level Modelling Study (ICWWS) 2018. Phase 1 is an update of the extreme water level estimation undertaken as part of the Irish Coastal Protection Strategy Study (ICPSS) between 2004 and 2013, which provided estimated water levels for a range of Annual Exceedance Probability (AEP) events at a series of estimation points around the Coast of Ireland.

The knowledge of extreme water levels around the coast is a key element in the assessment of the risk associated with coastal flooding and coastal change and the development of associated management strategies. It also allows informed decisions to be made on related coastal risk management schemes and provides the information to inform the design of such schemes. These extreme water levels are also critical for estimating and modelling the potential wave climate at the shoreline, as assessed under Phases 2 and 3 of this study, and for providing the joint probability information required to undertake wave overtopping, flood and other risk assessments, where relevant.

Due to the shape of the coast of Ireland and the presence of a number of shallow basins, both the tidal regime and the effects of wind on the water levels are complex, particularly in the Irish Sea. As such, simple interpolation of water levels along the coast and extrapolation to more extreme AEP events is not applicable or leads to low accuracy outputs. Therefore, a combination of analytical and numerical modelling techniques as developed and proven capable of predicting extreme tidal levels of various AEPs to the required accuracy in the ICPSS pilot study (Reference 1), were applied for this study.

The coast of Ireland was separated into assessment areas, as per the ICPSS, to ensure that the relevant methodologies, data and detail were applied to each section when undertaking the assessment. Numerical modelling considered either storm surge and tide levels independently or combined total water level as appropriate to each area of the coastline. Extreme value analysis was subsequently applied to the water level or surge data generated by the numerical models, allowing an estimation of extreme water levels of defined exceedance probability to be established along each area of coastline.

This report outlines how the extreme water levels in each assessment area were derived, indicating any differences in methodologies and data used, where relevant. The assessment areas are listed below and depicted in Figure 1.1.

- **North East Coast** – Dalkey Island to Omeath
- **South East Coast** – Dalkey Island to Carnsore Point
- **South Coast** – Carnsore Point to Bantry Bay
- **South West Coast** – Bantry Bay to Ballyvaghan Bay
- **West Coast** – Ballyvaghan Bay to Killala Bay
- **North West Coast** – Killala Bay to Lough Foyle

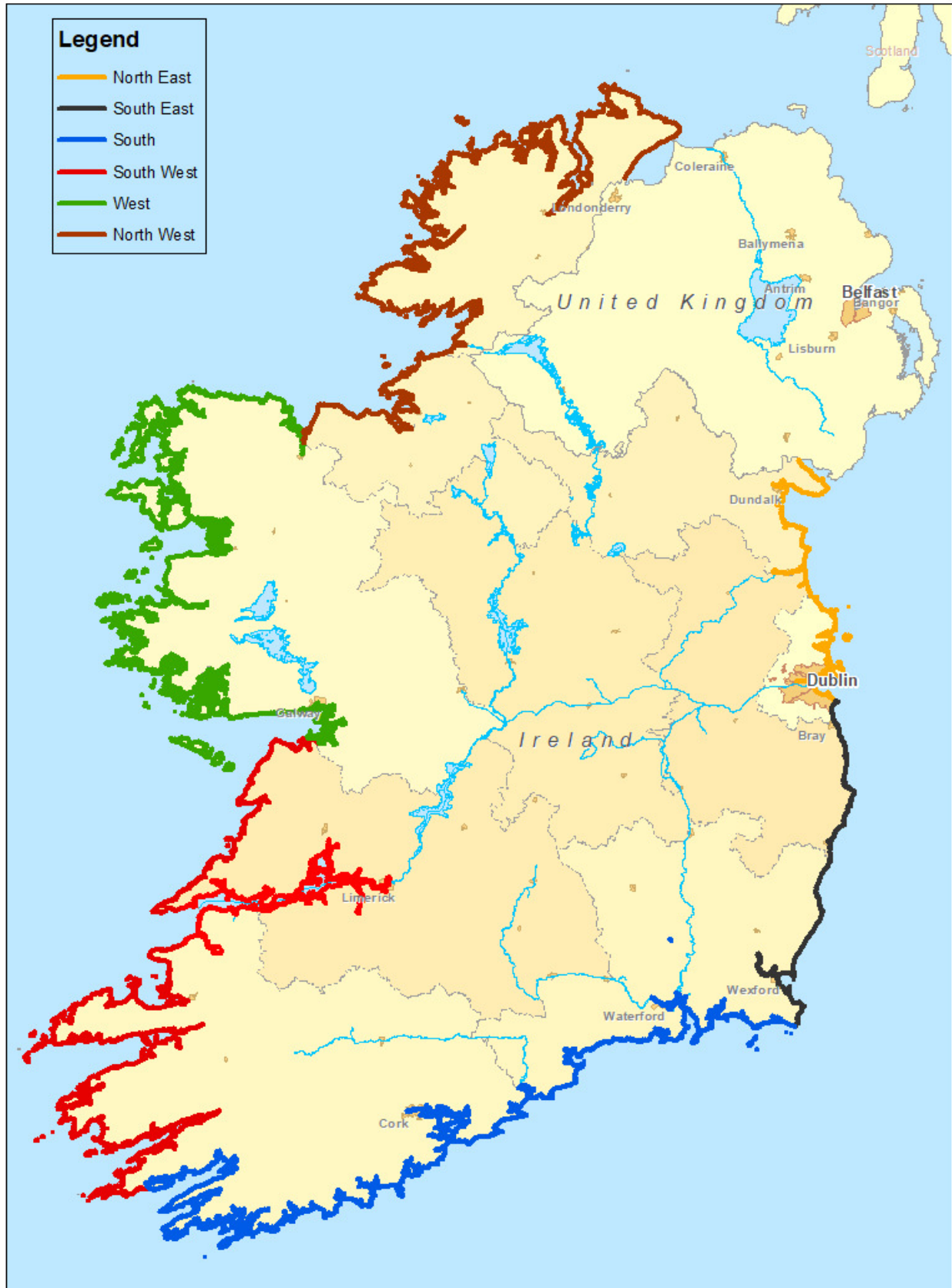


Figure 1.1: ICWWS 2018 Phase 1 Coastal Assessment Areas

2 KEY INFORMATION ON STUDY OUTPUTS

The Phase 1 study outputs include extreme sea level estimates for a series of estimation points around the coast of Ireland. These values are based on analysis and modelling, including:

- Numerical Modelling of combined storm surges and tide levels which was used to estimate extreme water levels along the coastline.
- Statistical extreme value analysis and joint probability analysis of both historic recorded tide gauge data and data generated by numerical modelling, which allowed an estimation of the extreme water levels of defined annual exceedance probability (AEP) to be established along the coastline.

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

- 1) The extreme levels refer to event probabilities in terms of a percentage Annual Exceedance Probability, or 'AEP'. This represents the probability of an 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) The extreme water levels refer to total water levels, i.e. water levels that 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.
- 3) The extreme water levels are inclusive of average allowances for 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). The period between these successive waves may vary between a few minutes to around two hours. Small seiches are not uncommon around the coast of Ireland.
- 4) 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).
- 5) The extreme water levels are produced to Mean Sea Level (MSL) and Ordnance Datum Malin (OD Malin) OSGM02 and OSGM15. MSL 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 OSGM02 and OSGM15 produced by the Ordnance Surveys of Great Britain (OS), Ireland (OSi) and Land & Property Services.
- 6) Although widely accepted methods have been used to derive the extreme levels, there are a number of limitations which should be considered when using this data for subsequent analysis. These include uncertainties in topographic and other survey data, inaccuracy in meteorological data, assumptions and / or approximations in tidal boundary 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, including assumptions and / or approximations relating to tide gauge data.
- 7) Taking account of the study limitations, the estimated accuracy of the total water levels presented in this report is $\pm 150\text{mm}$ relative to MSL, OD Malin OSGM02 and OD Malin OSGM15. Further information can be found in Section 5.3.

3 DATA SOURCES

While the availability of historic coastal water level records has improved since the completion of the ICPSS, there is still an absence of sufficient long term, historic, time series of water levels along the coast of Ireland to undertake an analysis based on such records alone. Consequently, in line with the approach adopted for the ICPSS, computational modelling was used to simulate water levels for a range of extreme events in order to generate a synthesised long term record of water levels around the national coastline. In order to do this, a range of data was required to perform the relevant simulations, as outlined in this chapter.

3.1 Tidal Data

For all model simulations undertaken as part of this study, the astronomic tides in the model area were driven by the oscillation of water levels along the open boundaries of the model domain. The Irish Seas Tidal Surge Model (ISTSM) developed by RPS under the ICPSS, has six open boundaries, five in the Atlantic and one in the English Channel. The time series of tidal elevations along these boundaries were generated using a global tidal model (DTU10) designed by the National Space Institute, Denmark. The DTU10 global tidal model is based on the prediction of tidal elevations using 10 semi-diurnal and diurnal tidal harmonic constants (as opposed to the United Kingdom Hydrographic Office approach which uses 4 to 6 harmonic constants). These constants were derived through the simulation of the effect of astronomic forces due to the sun and moon on the water surfaces. Figure 3.1 shows the amplitude of the M2 semi-diurnal (12.25hour) tidal harmonic constituent over the global model domain, whilst Figure 3.2 shows the same information over the extent of the ISTSM domain.

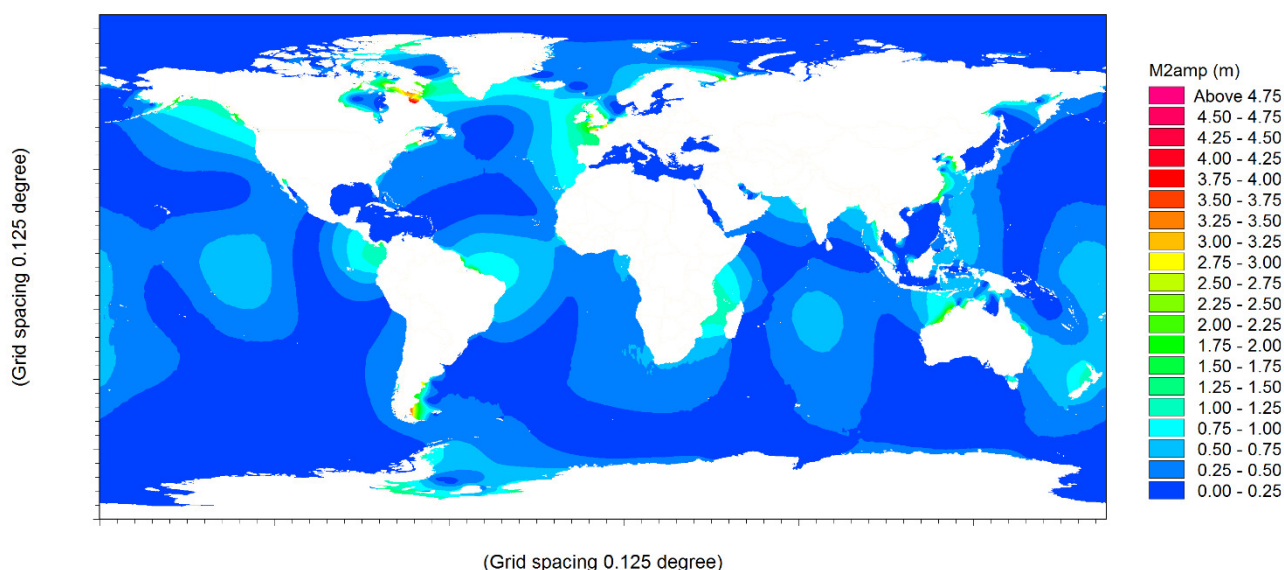


Figure 3.1: Tidal harmonic constituent for M2 amplitude for the DTU10 global model

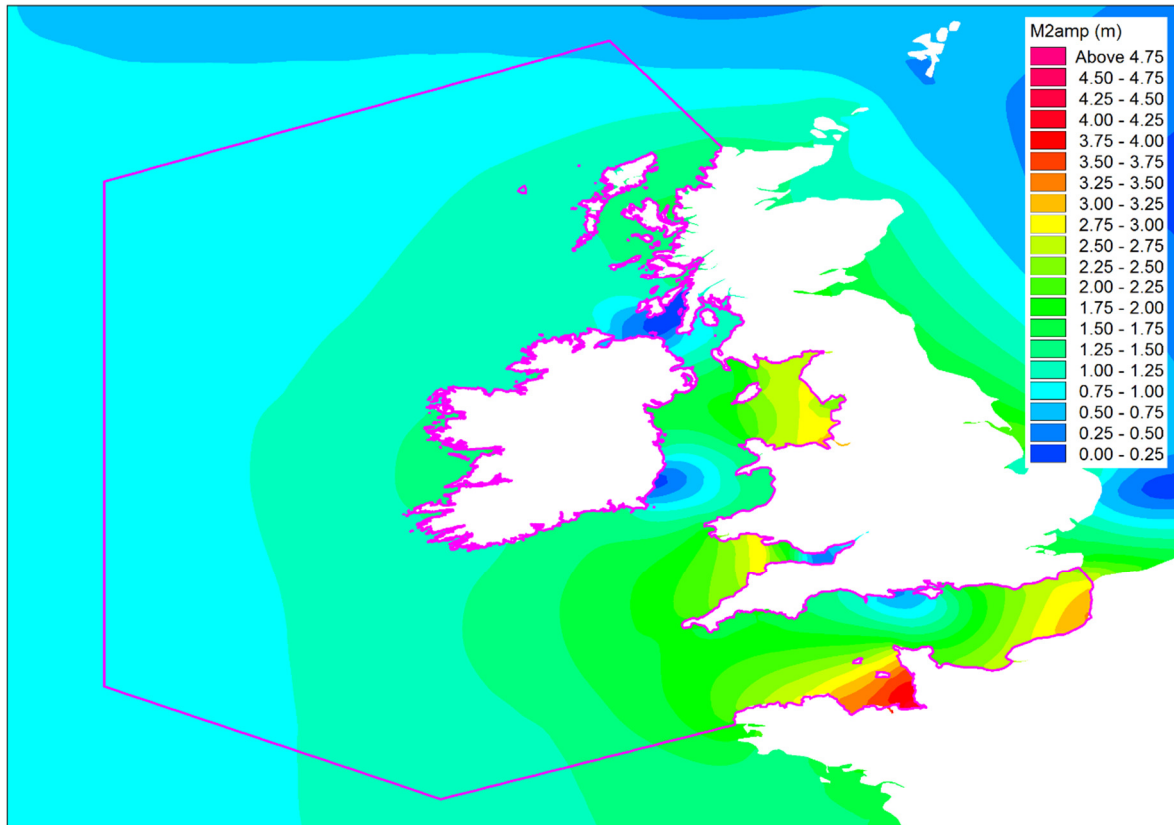


Figure 3.2: Tidal harmonic constituent for M2 amplitude for the ISTSM domain

3.2 Meteorological Data

The simulation of total water levels requires the consideration of atmospheric effects alongside astronomical tidal effects. Consequently wind speed and pressure data extending over the full model domain was required. For the ICPSS, the European Centre for Medium-Range Weather Forecasts (ECMWF) re- analysis and operational data was used to inform the meteorological element of the simulations, details of which can be found in the ICPSS reports (References 1-6).

For this update study, further meteorological input data for all newly identified storm events was obtained from the ECMWF, ERA5 global re-analysis model, which was made available in 2019 and thus differs from the meteorological data used for the ICPSS. For any original storm events which had to be re-run as part of this study due to the use of updated models, for example on the North East or South West coasts, the ICPSS meteorological data was re-used.

An example of the ECMWF meteorological data following conversion to the MIKE DFS2 format used in the simulations, is shown in Figure 3.3. The parameters applied to generate surge within the model are mean sea level atmospheric pressure and the 10 minute averaged 10 metre wind speeds (u and v component). These parameters were applied to the simulations on a 3 hourly basis for the relevant storm periods, as discussed under Section 5.4.

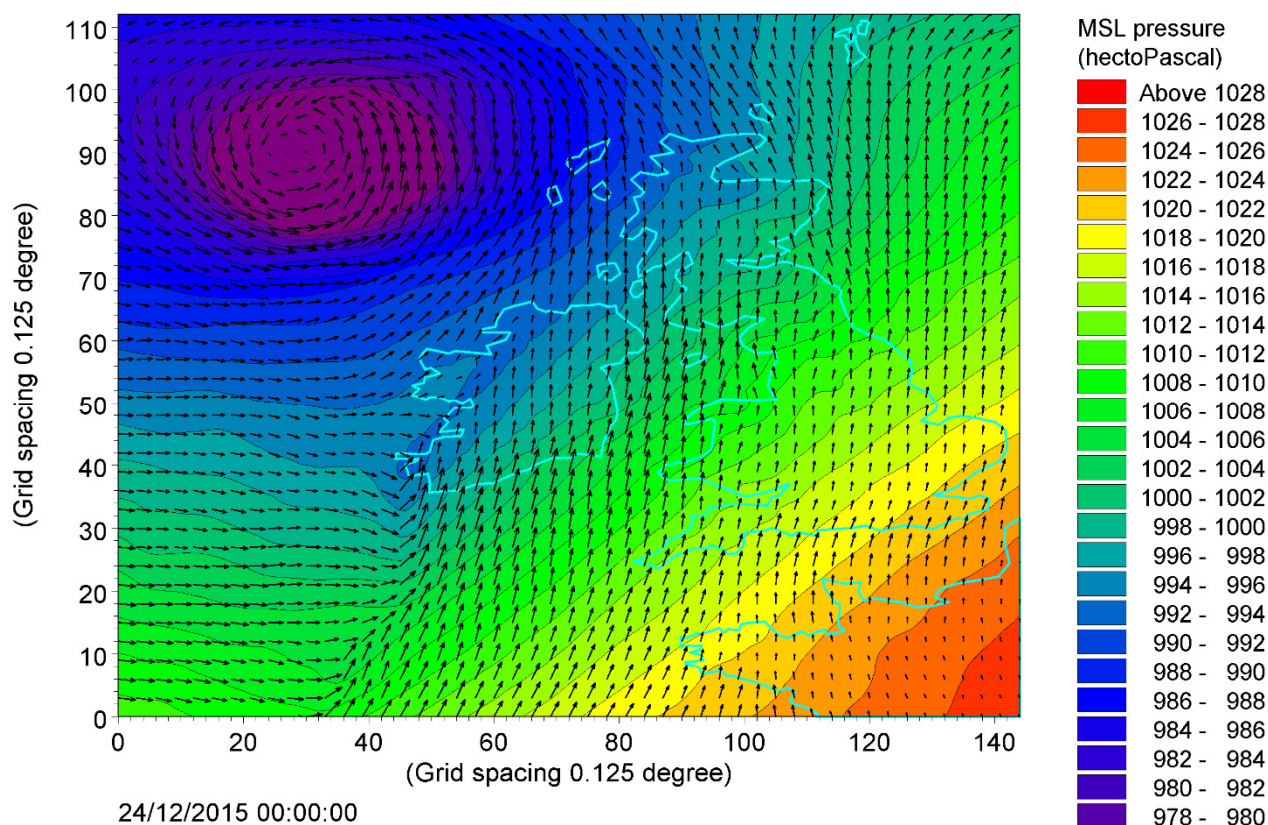
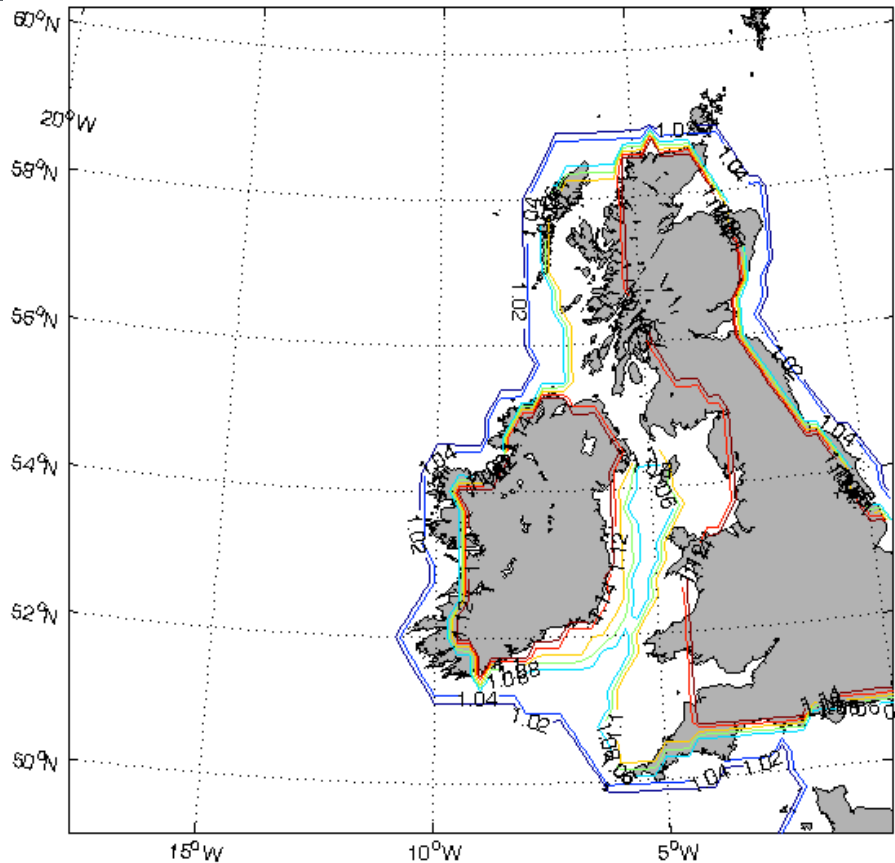


Figure 3.3: ECMWF sample meteorological data

During the ICPSS, it was established that due to the ECMWF atmospheric model resolution, the effect of land on wind speeds in the Irish Sea is more pronounced when compared with other coastal areas, which results in a minor under prediction of wind speeds in the Irish Sea. The wind fields in all ECMWF data sets were therefore subject to a small modification to take account of the under prediction, with the factor map used to adjust the wind speeds shown in Figure 3.4. This is in line with the adjustments made in the ICPSS.





- OPW LiDAR data (2006, 2012, 2013)
- OPW Hydrographic surveys (2012, 2015)
- Local hydrographic surveys carried out for numerous projects (1998 - 2013)
- MEDIN data (UK Hydrographic Office) (2012 – 2014)

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- LiDAR data for Tralee Bay (Bluesky, 2017)
- UK Admiralty Chart Data (C-Map of Norway)
- LiDAR data for the Fergus Estuary (OSi, 2012)

Figure 3.6 and Figure 3.7 show the coverage of the key survey datasets in the North East and South West areas of the Irish Seas model respectively, whilst the key datasets in the Shannon Estuary and Carlingford Lough models are shown in Figure 3.8 and Figure 3.9.

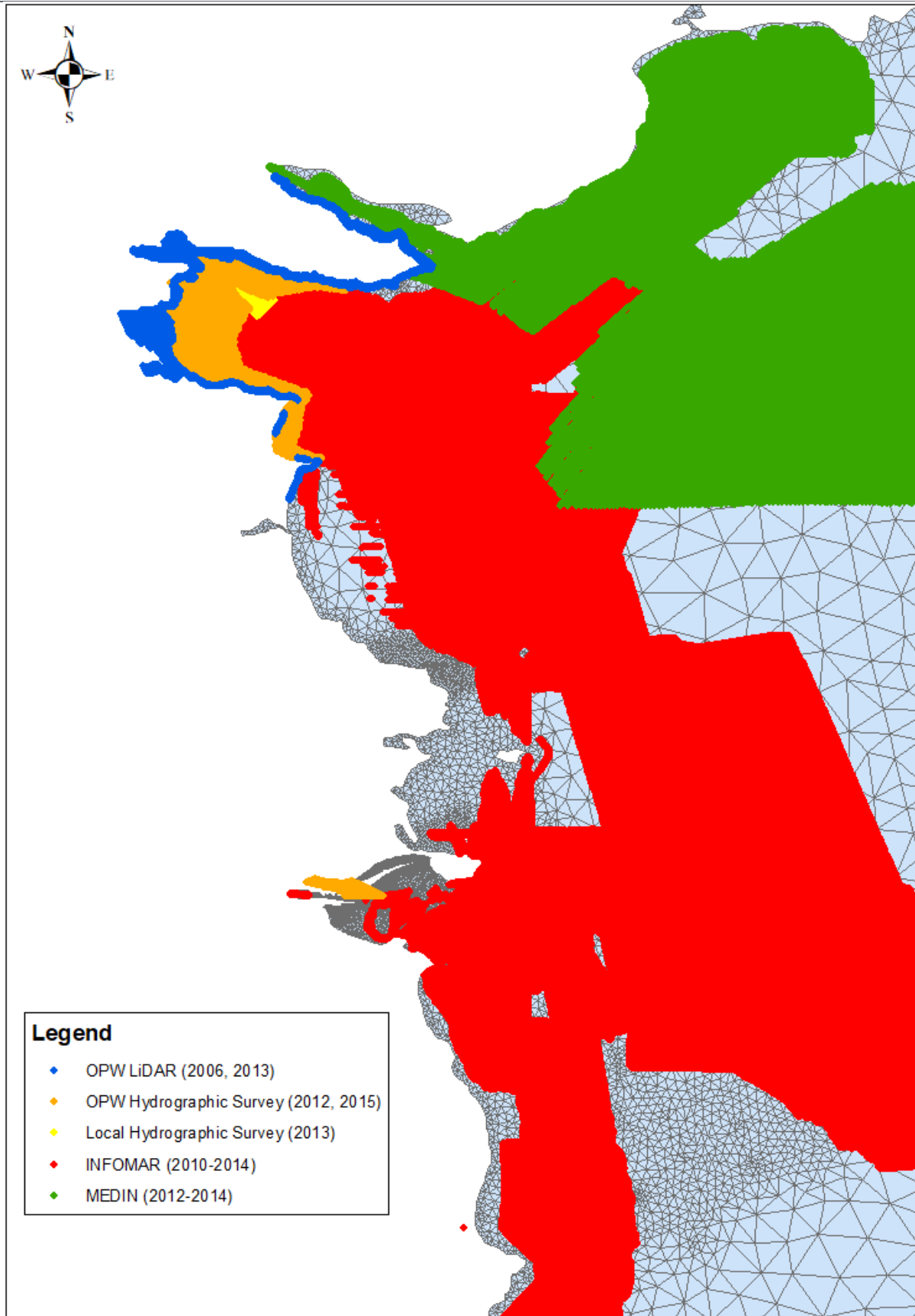


Figure 3.6: Coverage of key survey datasets in the North East area of the Irish Seas Model

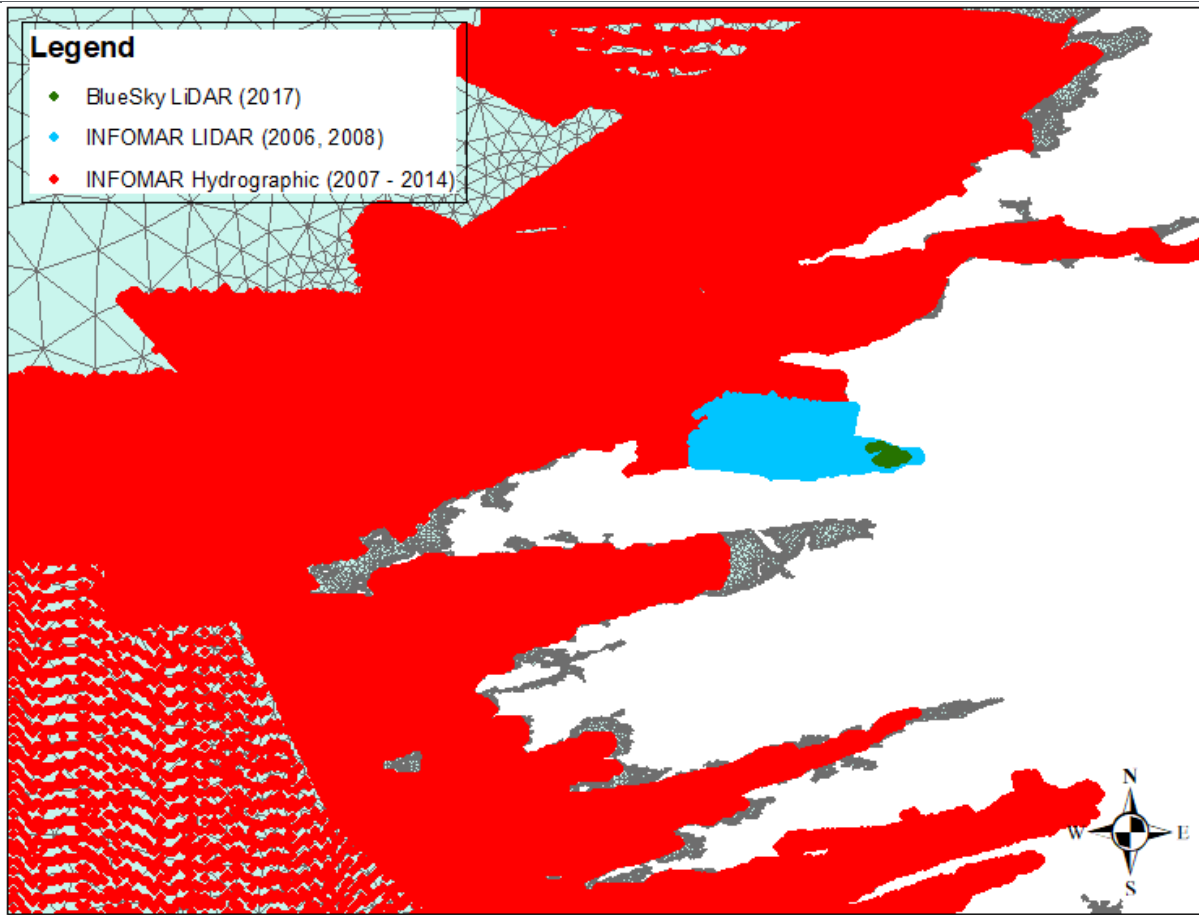


Figure 3.7: Coverage of key survey datasets in the South West area of the Irish Seas Model

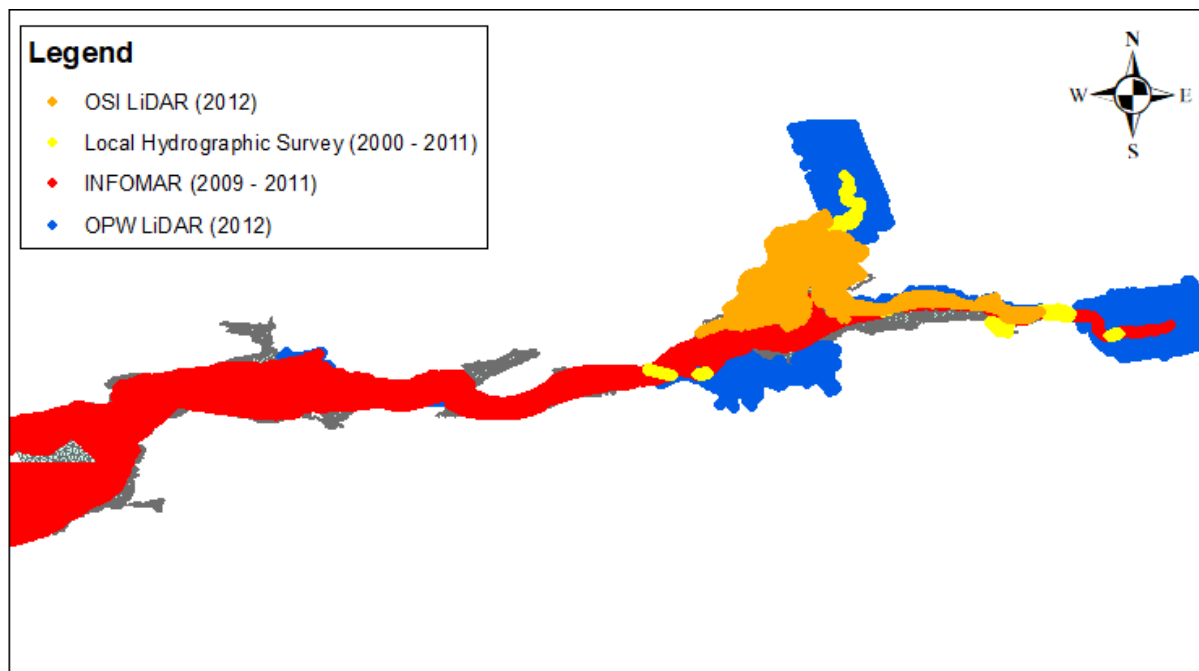


Figure 3.8: Coverage of key survey datasets in the Shannon Estuary Model

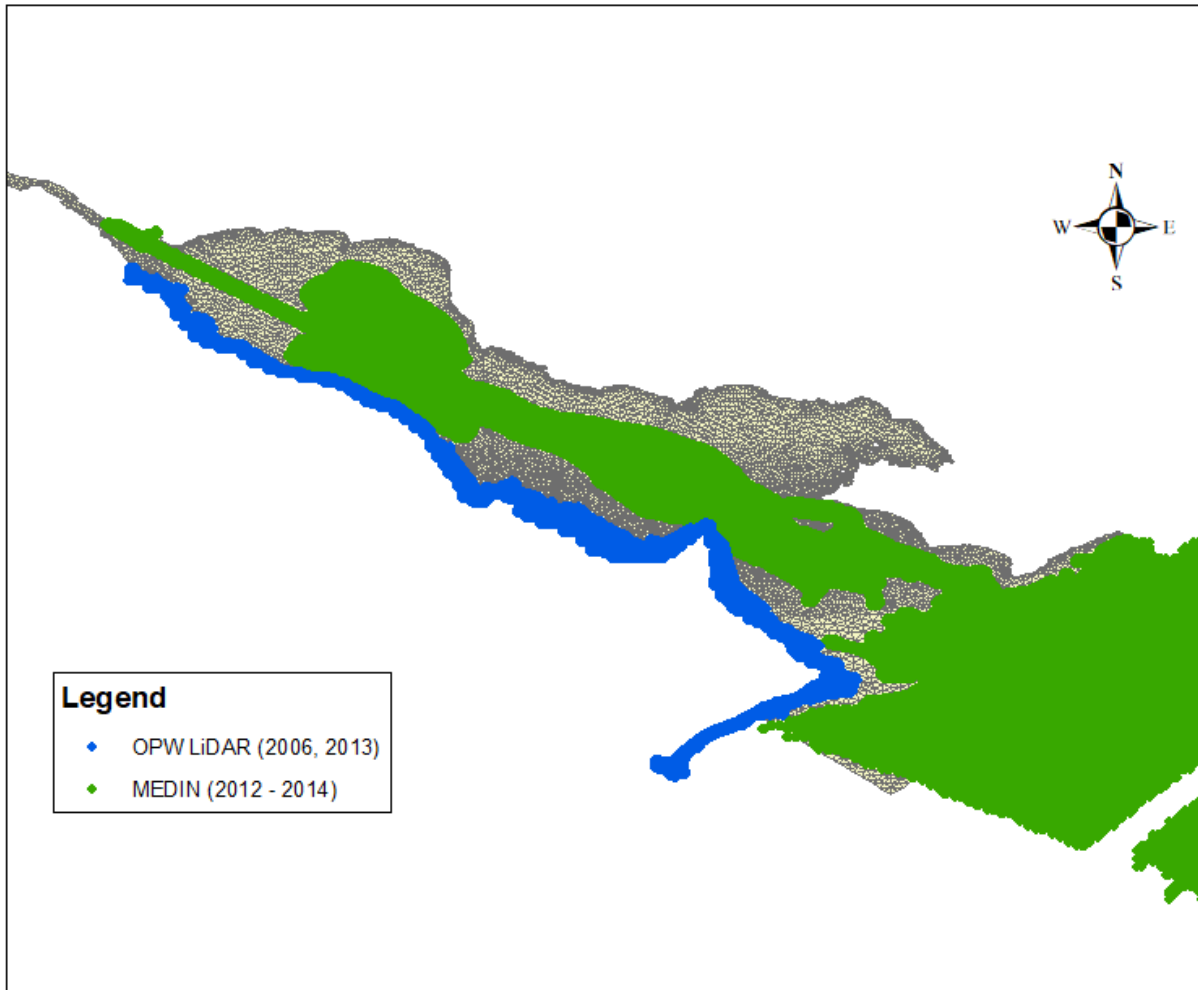


Figure 3.9: Coverage of key survey datasets in the Carlingford Lough Model

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

4 HISTORIC STORM SURGE SELECTION

This study considered both historic storm events identified under the ICPSS, and more recent events identified under this study. For the North East coast (including Carlingford Lough) and the South West coast (including the Shannon Estuary) the original storms were re-simulated using the updated models to provide consistent output for the statistical analysis, whereas for the remainder of the assessment areas, as there was no change to the underlying models only the more recent new events were simulated and combined with the ICPSS simulation outputs to form a complete dataset.

To identify historic storm surges which were relevant to each assessment area, the water level records from local gauges were reviewed, and all events with a recorded tidal level above a critical threshold at each gauge were identified. The dates of these events were then compared and significant storm events identified as those occasions when multiple gauges showed elevated water levels. Table 4.1 lists the gauges used in the ICPSS to identify storm events for each assessment area, along with those gauges used to identify the more recent events for this study. Note that more gauges were used to identify the events along the western coastal areas, as these gauges tended to have shorter or less reliable records than some of the more established gauges on the east coast. The use of a large range of gauges over the three western coastal areas, ensured that all relevant extreme storm events were identified.

Table 4.1: Gauges used in Storm Event Identification for each Coastal Assessment Area

	North East	South East	South	South West / West / North West
ICPSS	Dublin Port Holyhead Port Erin Portpatrick Quoile Barrier	Dublin Port Fishguard	Ballyteige Castlemaine Dunmore East Fiddown Marina	Balls Bridge Capeclear Carrigaholt Castlemaine Castletownbere Port Doon Bay Foyle Galway Port Killybegs Port Kilronan Malin Head Moneycashen Portrush Rossaveel Pier Tarbert
ICWWS 2018	Dublin Port Dundalk Port Holyhead Howth Harbour Port Erin Port Oriel Portpatrick	Arklow Harbour Dublin Port Fishguard Holyhead Wexford Harbour	Ballycotton Castletownbere Port Cobh Dunmore East Ringaskiddy NMCI	Balls Bridge Carrigaholt Castlemaine Castletownbere Port Fenit Foynes Inishmore Kilrush Lough Limerick Whelps

To model the full development of the storm surge, a period of approximately 4 days prior to each of the identified events and an additional 2 to 3 days after the day of the event was simulated. Therefore, at least 7 days of simulation was carried out for each surge event, with additional simulation time added as required. In a number of cases the surge event lasted a number of days or one low pressure field was followed immediately by another, also causing extreme water levels. In these cases the simulation period was extended to suit the combined event duration.

The storm events simulated in the ICPSS and ICWWS 2018 for each coastal assessment area are listed in Appendix A, along with the simulation durations and resolution of the corresponding meteorological data.

5 MODEL DEVELOPMENT

The RPS Irish Seas Tidal Surge Model (ISTSM) used to inform the ICPSS was again used and adapted where necessary to simulate the development of storm surges around Ireland for this study. The base model used mesh cells of varying sizes to cover the whole of the Irish seas, with a bespoke version developed for each coastal assessment area, focussing the detailed meshing in the relevant areas. The assessment areas are listed below, and align with the ICPSS.

- **North East Coast** – Omeath to Dalkey Island
- **South East Coast** – Dalkey Island to Carnsore Point
- **South Coast** – Carnsore Point to Bantry Bay
- **South West Coast** – Bantry Bay to Ballyvaghan Bay
- **West Coast** – Ballyvaghan Bay to Killala Bay
- **North West Coast** – Killala Bay to Lough Foyle

Where relevant, a number of smaller detailed models were also developed for some of the bays and estuaries around the coast of Ireland, namely, Carlingford Lough, Waterford Estuary, Cork Harbour and the Shannon Estuary. These areas were complex to model, with areas of rapidly changing bathymetry and coastline orientation, hence to produce a reliable tidal regime within the model, a significant number of computational cells were required in the mesh. To retain computational efficiency and stability in the Irish Seas Model, it was not possible to include sufficient detail in these areas, therefore, individual detailed models driven by boundary conditions extracted from the Irish Seas Model were developed for each area, allowing the required detail in the meshing to be included.

5.1 Modelling System

All hydrodynamic modelling simulations undertaken as part of this study made use of the MIKE21 flexible mesh modelling system which is a 2-dimensional, depth averaged hydrodynamic model developed to simulate the water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal areas. The water levels and flows are resolved on a triangular grid when provided with the bathymetry, bed resistance coefficient, wind field, hydrodynamic boundary conditions, etc. The system solves the full time-dependent non-linear equations of continuity and conservation of momentum (depth-integrated incompressible Reynolds averaged Navier-Stokes equations) using an implicit Alternating Direction Implicit (ADI) finite difference scheme of second-order accuracy. The forcing mechanisms available in the models include wind shear stress at the surface, barometric pressure gradients, Coriolis forces, momentum dispersion (e.g. through the Smagorinsky formulation) and flooding and drying.

5.2 Model Bathymetries

The ISTSM used in this study covers an area of 18° longitude and 13.5° latitude as shown in Figure 5.1. The base model extends from the North-western coast of France including the English Channel as far as Dover to 16° West into the Atlantic, including the Porcupine Bank and Rockall. The model also extends from the Northern part of the Bay of Biscay to just south of the Faeroes Banks in the North. Overall the ISTSM covers the Northern Atlantic Ocean up to a distance of 600km from the coast of Ireland.

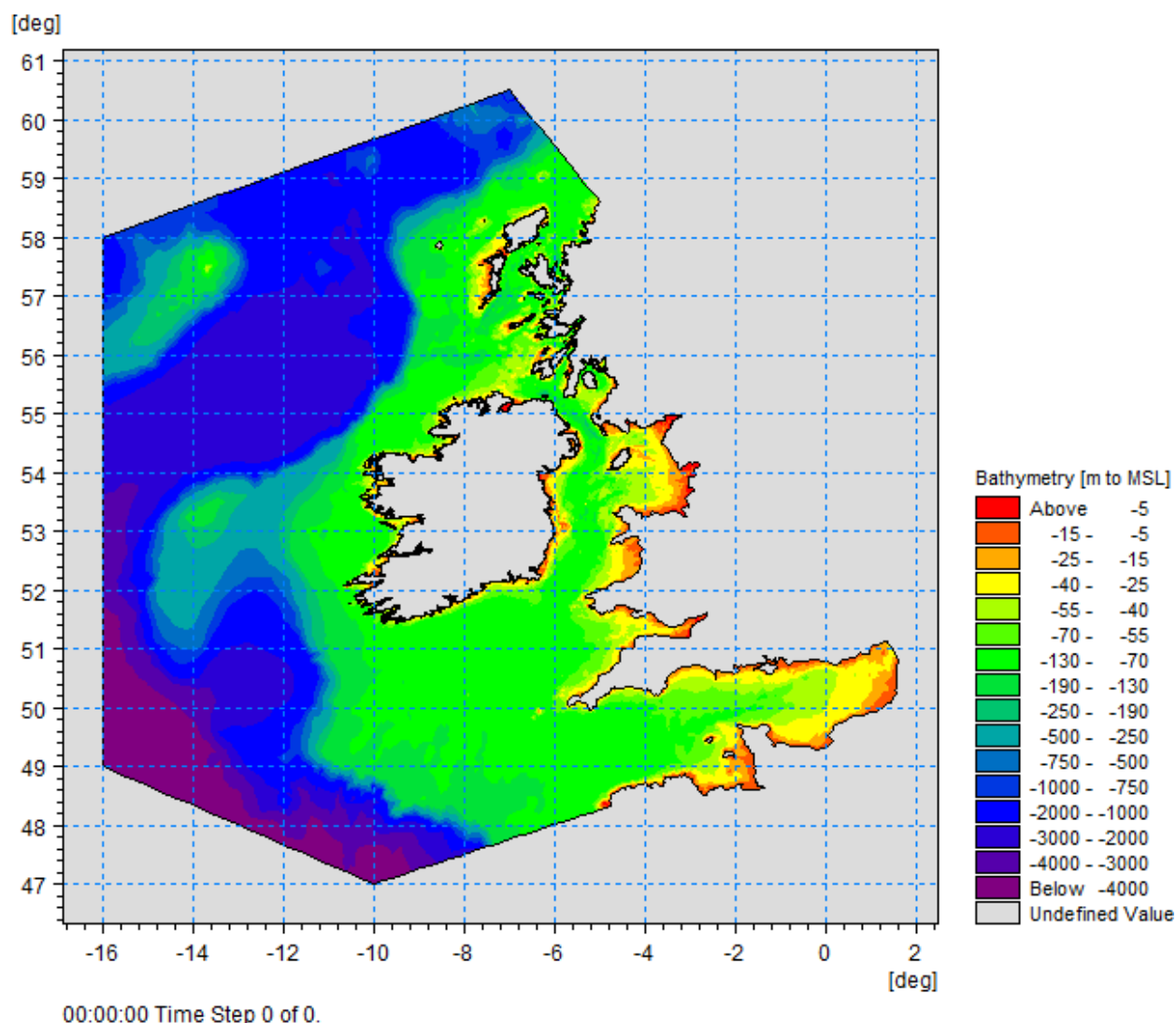


Figure 5.1: Extent of Irish Seas Tidal Surge Model (ISTSM)

The ISTSM utilises flexible mesh technology allowing the size of the computational cells to vary depending on user requirements, and hence assessment area. To adequately represent the variable bathymetry, each of the model meshes were generated and refined in regions of most importance to ensure satisfactory model performance for the six areas. Thus the models provide greater detail along the shoreline and over banks in the relevant assessment area when compared to other parts of the model domain. Along the Atlantic boundary, the models feature a mesh size of 13.125' (24km) compared to circa 150-200m adjacent to the shoreline in each assessment area.

5.2.1 Carlingford Lough

As the entrance to Carlingford Lough is relatively complex a more detailed analysis was performed in this area, using a separate higher resolution flexible mesh model. For this area the new detailed model intended for use in the Carlingford Phase 3 study was also employed at this stage with all events re-simulated rather than just the additional events. Figure 5.2 shows the extent and bathymetry of the model.

Suitable boundary conditions for this model were obtained by extracting the surface elevations from the ISTSM for the North East coast and applying them as boundary conditions to the Carlingford Lough model.

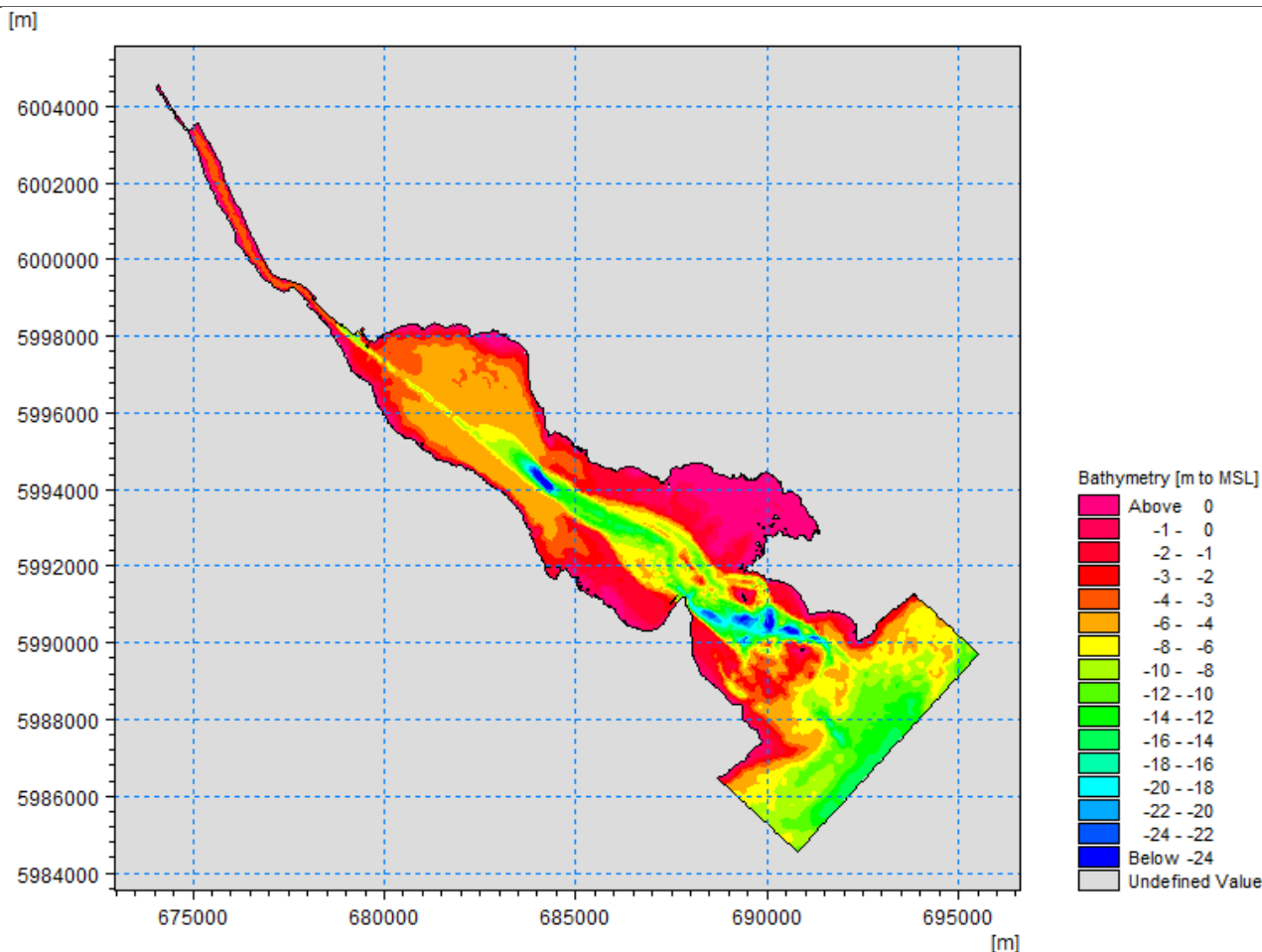


Figure 5.2: Extent and Bathymetry of the Carlingford Lough Model

5.2.2 Waterford Estuary

A detailed analysis was performed in the Waterford Estuary, as per the ICPSS, with the additional events simulated using the original detailed model from the ICPSS. The Waterford Estuary models are comprised of two rectangular gridded meshes; an outer estuary model with grid spacing of 135 metres, used to provide the boundary conditions for an inner, more detailed estuary model, with a resolution of 45 metres. Figure 5.3 and Figure 5.4 show the extent and bathymetry of the Outer and Inner Waterford Estuary models respectively.

Suitable boundary conditions for the outer model were obtained by extracting surface elevations from the ISTSM for the South coast and applying them as boundary conditions to the Outer Waterford Estuary model.

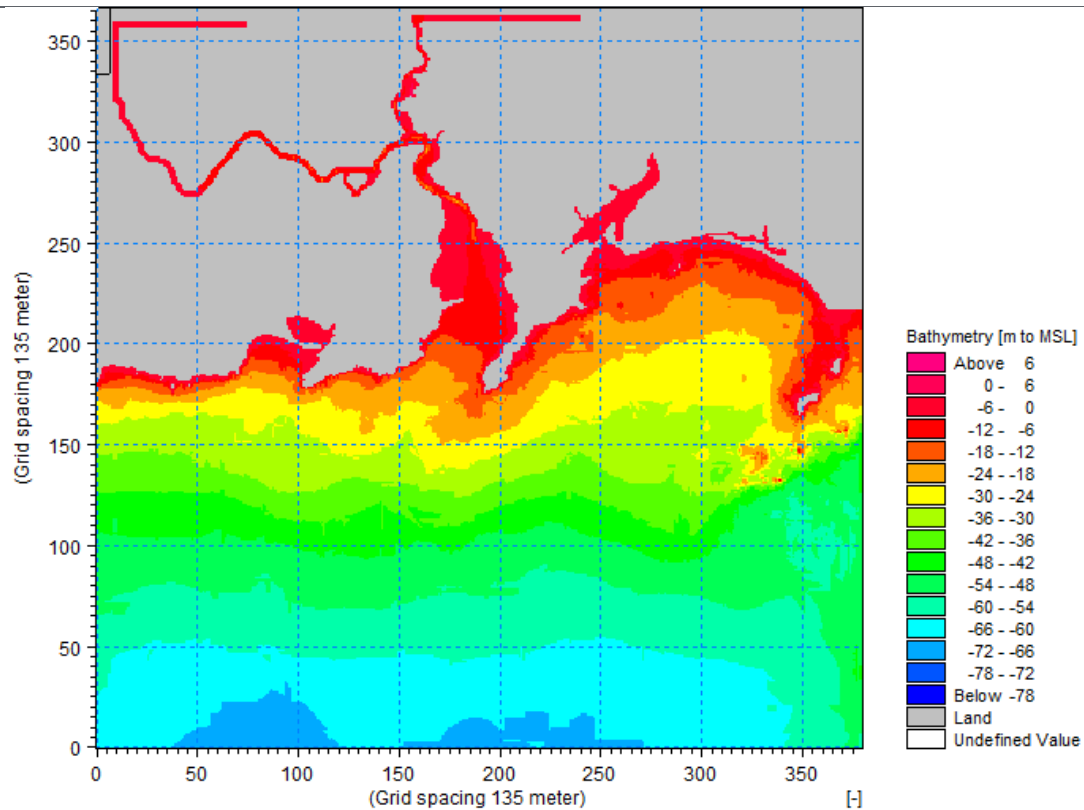


Figure 5.3: Extent and Bathymetry of the Outer Waterford Estuary Model

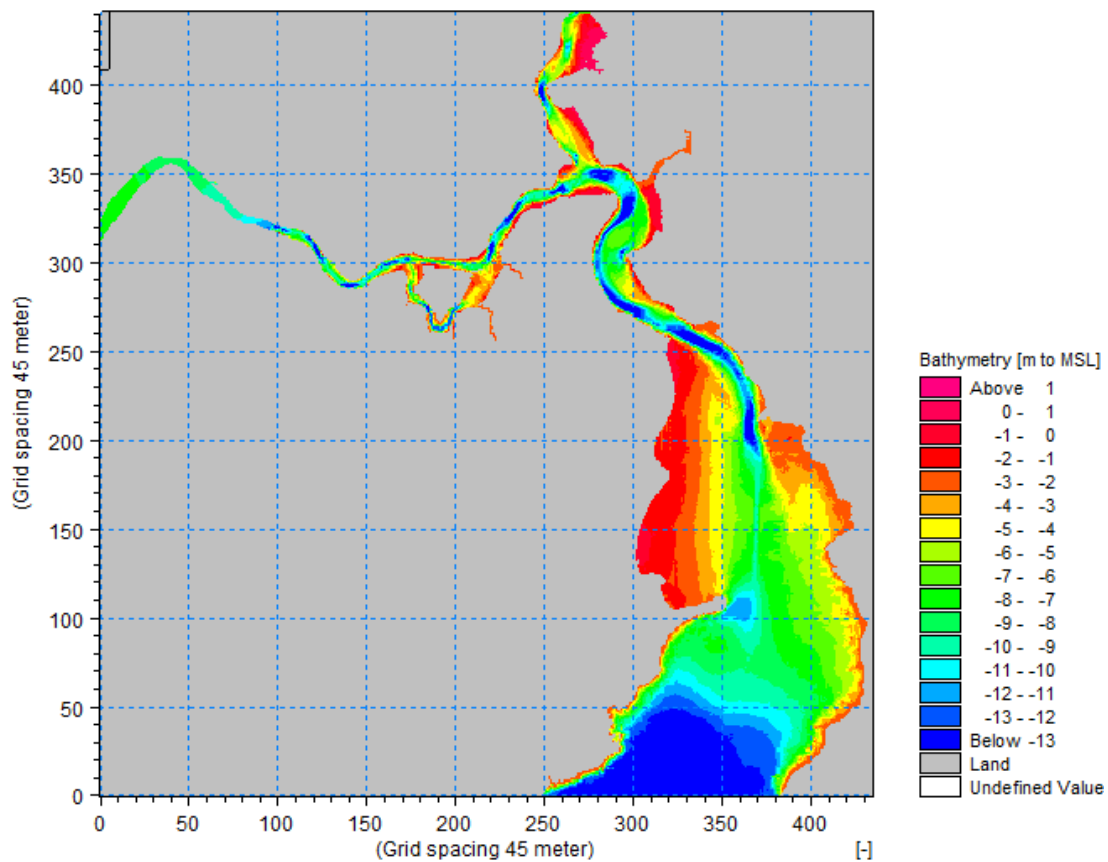


Figure 5.4: Extent and Bathymetry of the Inner Waterford Estuary Model

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5.2.3 Cork Harbour

A detailed analysis was performed in Cork Harbour, as per the ICPSS, with the original detailed ICPSS model again being used to simulate the recent storm events for this study. The Cork Harbour model used a rectangular gridded mesh of 60 metre spacing. Figure 5.5 shows the extent and bathymetry of the Cork Harbour model.

Suitable boundary conditions for this model were obtained by extracting surface elevations from the ISTSM for the South coast and applying them as boundary conditions to the Cork Harbour model.

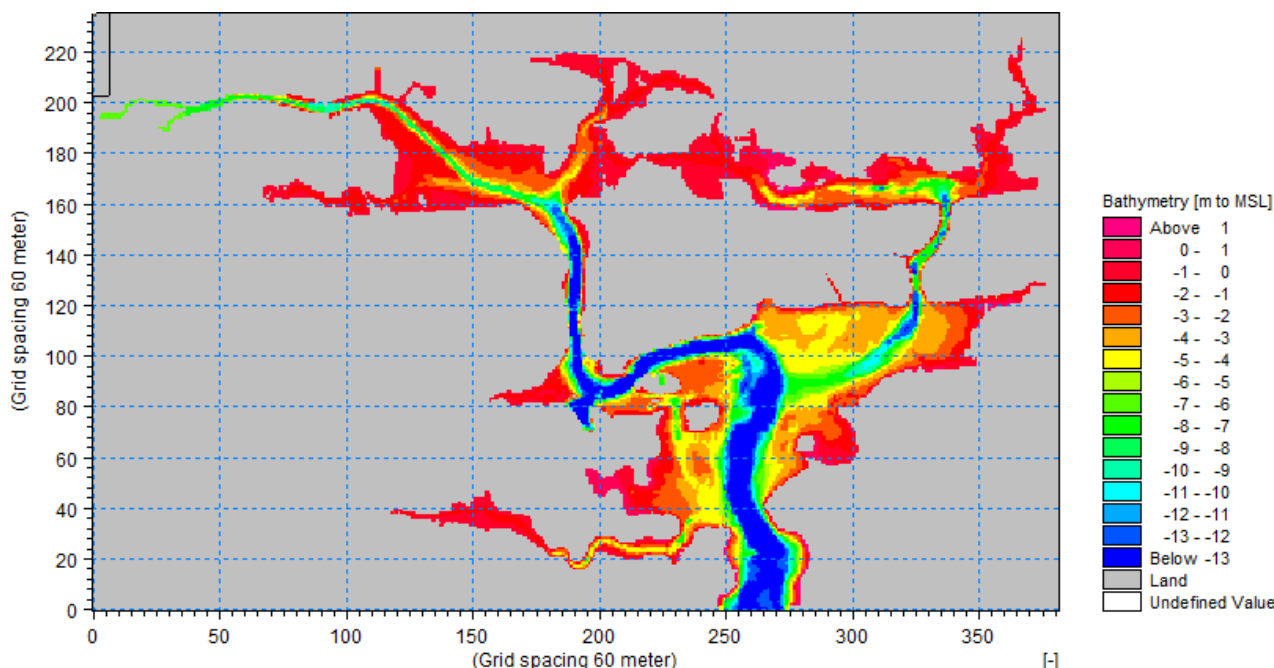


Figure 5.5: Extent and Bathymetry of the Cork Harbour Model

5.2.4 Shannon Estuary

To provide more accurate water levels in the Shannon Estuary, a separate more detailed flexible mesh model was used to simulate the historic water levels. For this study the detailed model of the Shannon Estuary developed for the subsequent ICWWS Shannon/Bunratty Phase 3 study was employed with all events re-simulated. Figure 5.6 shows the extent and bathymetry of the model.

Suitable boundary conditions for this model were obtained by extracting surface elevations from the ISTSM for the South West coast and applying them as boundary conditions to the Shannon Estuary model.

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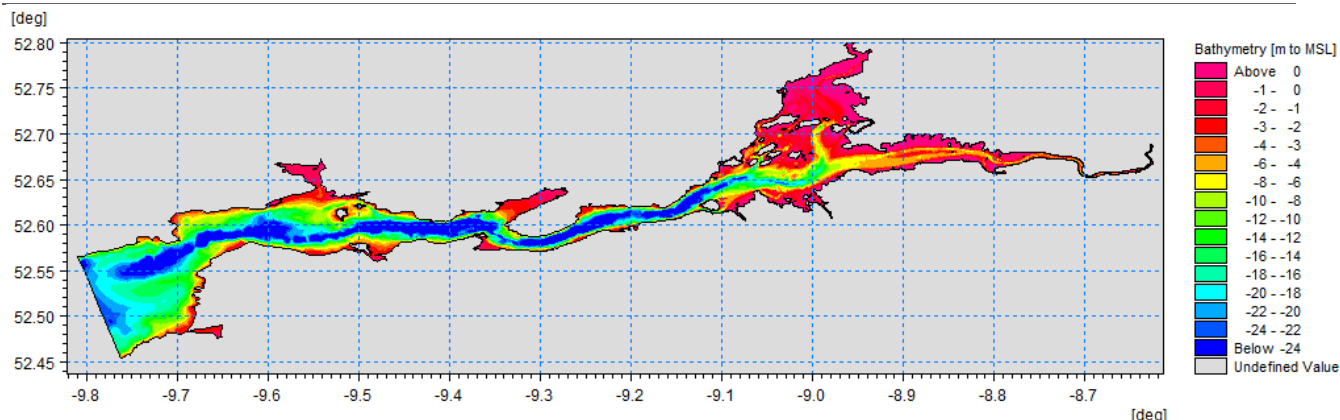


Figure 5.6: Extent and Bathymetry of the Shannon Estuary Model

Most events simulated for the South West coast were also simulated for the Shannon Estuary, with the exception of a small number of events which didn't yield particularly large water levels (less than 2.5 metres to MSL) at the boundary of the Shannon Estuary model. Modelled events for the Shannon Estuary can be viewed in Appendix A.

5.3 Model Validation

In the majority of cases, namely the South East coast, South coast, West coast and North West coast and the detailed Cork Harbour and Waterford Estuary models, the meshes used in the modelling were not updated. These meshes were extensively tested and calibrated during the ICPSS prior to the simulation of storm surges and shown to give good correlation with tidal water levels along the coast.

The ICPSS base model was calibrated against a set of tidal predictions over a period of more than 30 days. A detailed description of the model set-up, the boundary conditions, model constraints and the calibration and validation with tidal events can be found in the ICPSS calibration report (Reference 7). Further validation exercises were undertaken for each of the bespoke meshes for the assessment areas, detail of which can be found in the ICPSS reports (References 1-6).

As the North East, South West, Shannon Estuary and Carlingford Lough models have now been updated, further validation was undertaken to ensure the models continued to produce results within the expected tolerances for this study. This generally involved a comparison of modelled water levels to existing tide gauge data, during a storm event, or in some cases, where gauge data was lacking using Admiralty data to generate predicted astronomic tides to compare with modelled tides, when meteorological influences were minimal. It is the tidal element of the hydrodynamic modelling that is typically most difficult to perfect, rather than the surge residual, and thus referencing the Admiralty data provided a good insight into the validity of the modelling.

Furthermore, the meshes developed within this study are closely related to the current model used to provide Tidal and Storm Surge Forecasting Services for the Coast of Ireland for the OPW. This mesh has been rigorously tested to optimise the accuracy and reliability of forecast water levels simulated on a daily basis, thus adding confidence to the functionality of the models for this study. Further information on the forecast ISTSM validation can be found in the most recent evaluation report (Reference 8).

Plots from this validation exercise can be found in Appendix B for each of the models (North East, South West, Shannon Estuary and Carlingford Lough). As the Marine Institute and OPW tide gauge data are typically provided to OD Malin (OSGM15) datum and each of the assessment area models yield results to Mean Sea Level (MSL), to compare the data, appropriate conversion estimations were applied based on the work undertaken during Phase 4 of this study.

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It was anticipated that the assessment area models would estimate water levels within a tolerance of $\pm 180\text{mm}$, as per the ICPSS, however due to an improvement in both the modelling and the conversion from MSL to OD Malin, the validation exercise has shown the tolerance to be improved for all estimation points in the ICWWS 2018. The work undertaken in Phase 4 enabled a reliable conversion of the modelled water levels from MSL to OD Malin (OSGM15) for direct comparison with the gauge data which was provided to OD Malin (OSGM15) for the North East, South West, and Carlingford Lough model validation. As the Shannon Estuary model validation was based on Admiralty data and gauge data without an accurate relationship to OD Malin (OSGM15), the comparison was made using levels to MSL.

As can be seen from the 'Water Level Upper Bound' and 'Water Level Lower Bound' tolerance envelopes on the plots in Appendix B, generally all modelled results lie well within the tolerance of $\pm 150\text{mm}$. It is the peak water levels which are critical to this study, and these generally align well. More often it is the low water levels where discrepancies may be found, for example Whelps in the Shannon Estuary model, however low water levels are less relevant to this study, as the aim is to generate extreme event information. Likewise, the modelled water levels at Fenit during high neap tides appear marginally over-predicted, however these less extreme water levels would not be relevant to this study. There are a number of gauge comparisons, where at times the tolerance is reached or marginally exceeded, for example, Dublin, Carrigaholt and Galway Port, although oscillation within the gauge data is partly responsible. Due to the geographic variability of these gauges, a tolerance of **$\pm 150\text{mm}$** has been set for all estimation points, to ensure an appropriate level of confidence is applied around the coast of Ireland, even though there are many locations where the tolerance may be much smaller.

There remains however some uncertainty in the model accuracy within the upper Shannon Estuary, as the available gauges in this area drown out during extreme tidal events. Consequently it is not currently possible to verify the upper reaches of the Shannon Estuary model for extreme tidal levels, although the individual components, astronomical tide and storm surge have been verified separately by considering records for periods of no storm activity and surge events that corresponded to low water times respectively. Hence while the model has been demonstrated to replicate the normal tides throughout the estuary and the propagation of surges at periods of low tide the correct propagation of surges on high tides has not been proven.

However, there is a much greater degree of confidence in the Shannon Estuary water levels estimated during this study, in comparison with those estimated in the ICPSS. The updated ICWWS 2018 model includes bathymetry data for the Fergus Estuary, the absence of which was a significant limitation of the ICPSS model. Furthermore, although there is uncertainty in the datums, the ICWWS 2018 Shannon Estuary model was validated, albeit to MSL, and found to correlate well with three tide gauges that were not available for the ICPSS (Carrigaholt, Foyne and Whelps).

In conclusion, each model showed good correlation with the majority of the tide gauge data at the various locations where records were suitable for comparison. The models were therefore considered successfully validated and fit for the purpose of simulating storm surge water levels and predicting extreme water levels in the relevant areas, with all results lying within the tolerance of **$\pm 150\text{mm}$** for the study, with the exception of a small number of exceedances as discussed above.

5.4 Model Simulations

The ISTSM meshes and detailed meshes were used to simulate storm surge events relevant to each coastal assessment area, which had occurred over recent years. The North East, South West, Shannon Estuary and Carlingford Lough models were subject to bathymetric update and hence were also used to re-simulate the events modelled as part of the ICPSS. A full list of the historic events simulated for each area is available in Appendix A.

For the complex north east and south east coasts two simulations were run for each storm surge period; one with tidal components only and the other with both tidal and storm surge components. This approach was not feasible for the south and west coast simulations, due to the lack of sufficient information to allow an accurate assessment to be made of the joint probability of occurrence of tidal and surge events. Thus, for the exposed Atlantic coastlines the models were run using combined tidal and surge components only.

Where tidal and surge elements were simulated separately (North East and South East coasts), the surge component at all relevant points could be directly derived and separated from the tidal elevations (surge

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residual). As a result the extreme water levels were derived as a combined probability of extreme tidal elevation and surge component. Correlation coefficients for use in the joint probability exercise to combine the two elements remained the same as those of the ICPSS, as discussed under Section 6.5. The existence of long term gauge data and the proximity to other established correlation sites on the UK coastline, as noted in the DEFRA / Environment Agency report on joint probability (Reference 9) allowed for a reliable derivation of correlation coefficients for the east coast.

Where tidal and surge elements were simulated in combination (South, South West, West, North West, Waterford, Cork, Shannon and Carlingford Lough), one simulation was run for each event, incorporating both tidal and storm surge components, with the extreme water levels being the direct output.

5.5 Model Estimation Points

From the various storm simulations, time series of the water surface elevations were extracted at the model estimation points around the coast of Ireland. The positions of these estimation points were selected based on considerations of the shape of the coastline, which might affect surge levels, in addition to proximity to areas potentially vulnerable to coastal flooding. The estimation points for this update study remained the same as for the ICPSS and are presented in Appendix C.

For the North East and South East coasts, in conjunction with the extraction of the tidal levels, the surge residual was also calculated for each estimation point and from the resulting time series the total maximum water level and the maximum surge residual for each storm was derived. In this context, it was assumed that any atmospheric depression combined with strong winds could be considered as an independent storm event for the statistical analysis, if at least 4 days had passed between surge events and if the surge residual had fallen close to or below zero.

6 STATISTICAL ANALYSIS

6.1 Extreme Value Analysis

Extreme value analysis (EVA) was undertaken by fitting theoretical probability distributions to the peak water levels extracted from the results of the model simulations. A partial duration series, also known as peak over threshold model, was used to select the largest events which occurred within the dataset. The selection can be made on the basis of a fixed number of the largest values or by applying a threshold level over which the events are selected for inclusion into the data series.

Candidate probability distributions were fitted to the data, with several distributions investigated as follows:

- Weibull,
- Generalised Pareto,
- Gamma/Pearson Type 3,
- Log-Pearson Type 3,
- Log-normal,
- Exponential,
- Truncated Gumbel.

For the estimation of the parameters relating to the probability distributions, generally three methods were applied; the method of moments, the method of L-moments and maximum likelihood method.

The goodness of fit of the resulting distributions was tested using five statistical methods; Chi-squared, Kolmogorov-Smirnov test, standardised least squares criterion, probability plot correction co-efficient and Log-likelihood measure.

The uncertainty of these distributions was also evaluated by application of a Jack-knife re-sampling technique. With this technique the entire data set of n events is re-sampled $n-1$ times. Each time one of the events is excluded and the distribution is fitted to the remaining $n-1$ events using the same method. From the resulting distributions the values for given return periods are derived and the average and the standard deviation determined. These values are referred to as the averaged estimates and the standard deviation of the estimates. The difference of the averaged estimate and the estimated value initially derived provides a measure of the convergence of the statistical analysis (i.e. if the analysis covered a long enough period) and the confidence limits of the values are given by the standard deviation. However even with the use of this technique the accuracy of the estimations diminishes with increasing return period and in general it is advised to be wary of any estimations where the return period is more than three times the length of the record period on which the analysis is based.

Extreme value analysis was carried out on the statistical data in two ways. For most of the coastline the processes combining to create extreme water levels can be considered as random, in which case the probability functions were fitted to the entire set as a whole. This was the case for the South coast (including Cork and Waterford), along with the three western coastal areas (including the Shannon Estuary), where the analysis was undertaken on total water level.

In the case of the water levels on the North East and South East coasts, the probability of occurrence or exceedance was derived for astronomic tides and surge separately, and through a correlation factor the two were then combined in a joint probability analysis. This allowed for the fitting of separate distributions for each parameter (astronomic tide and surge).

In shallow water areas, for example, Carlingford Lough or Wexford Harbour, where the tidal currents are much stronger, the current and surge conditions are strongly dependent and the total water levels had to be

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evaluated and probability distributions plotted directly. The approaches adopted in all areas mirrored those of the ICPSS.

6.2 Extreme Value Analysis of Total Water Level

The extreme value analysis of total water level was undertaken as described in the previous section for all estimation points on the South, South West, West and North West coasts, including the Shannon Estuary, Cork Harbour and Waterford Estuary. In addition, this approach was applied in areas of higher current – surge interaction on the South East and North East coasts, namely Carlingford Lough (for estimation points NE27 to NE29) and Wexford Harbour (for estimation points SE31 to SE34).

The best fitting results were obtained by using the threshold or fixed location parameter method for selecting data. The most successful candidate distributions and respective methods used to evaluate the parameters are given in Table 6.1 for each relevant coastal area.

Table 6.1: Best fitting Distributions of Total Water Level for relevant Coastal Areas

Coastal Area	Distribution	Method
Carlingford Lough	Truncated Gumbel	Maximum Likelihood
Wexford Harbour	Truncated Gumbel	Maximum Likelihood
South Coast	Truncated Gumbel	Maximum Likelihood
Waterford Estuary	Truncated Gumbel	Maximum Likelihood
Cork Harbour	Truncated Gumbel	Maximum Likelihood
South West Coast	Truncated Gumbel	Maximum Likelihood
	Gamma / Two parameter Weibull	Method of Moments, Maximum Likelihood, Method of L-moments
Shannon Estuary	Truncated Gumbel	Maximum Likelihood
West Coast	Truncated Gumbel	Maximum Likelihood
	Gamma	Method of Moments, Maximum Likelihood, Method of L-moments
North West Coast	Truncated Gumbel	Maximum Likelihood

The extreme water levels were evaluated for return periods ranging from less than 1 year to 1 in 1000 year. A sample extreme value analysis plot is shown in Figure 6.1, illustrating the Truncated Gumbel Maximum Likelihood method, best fit estimation of probability distribution.

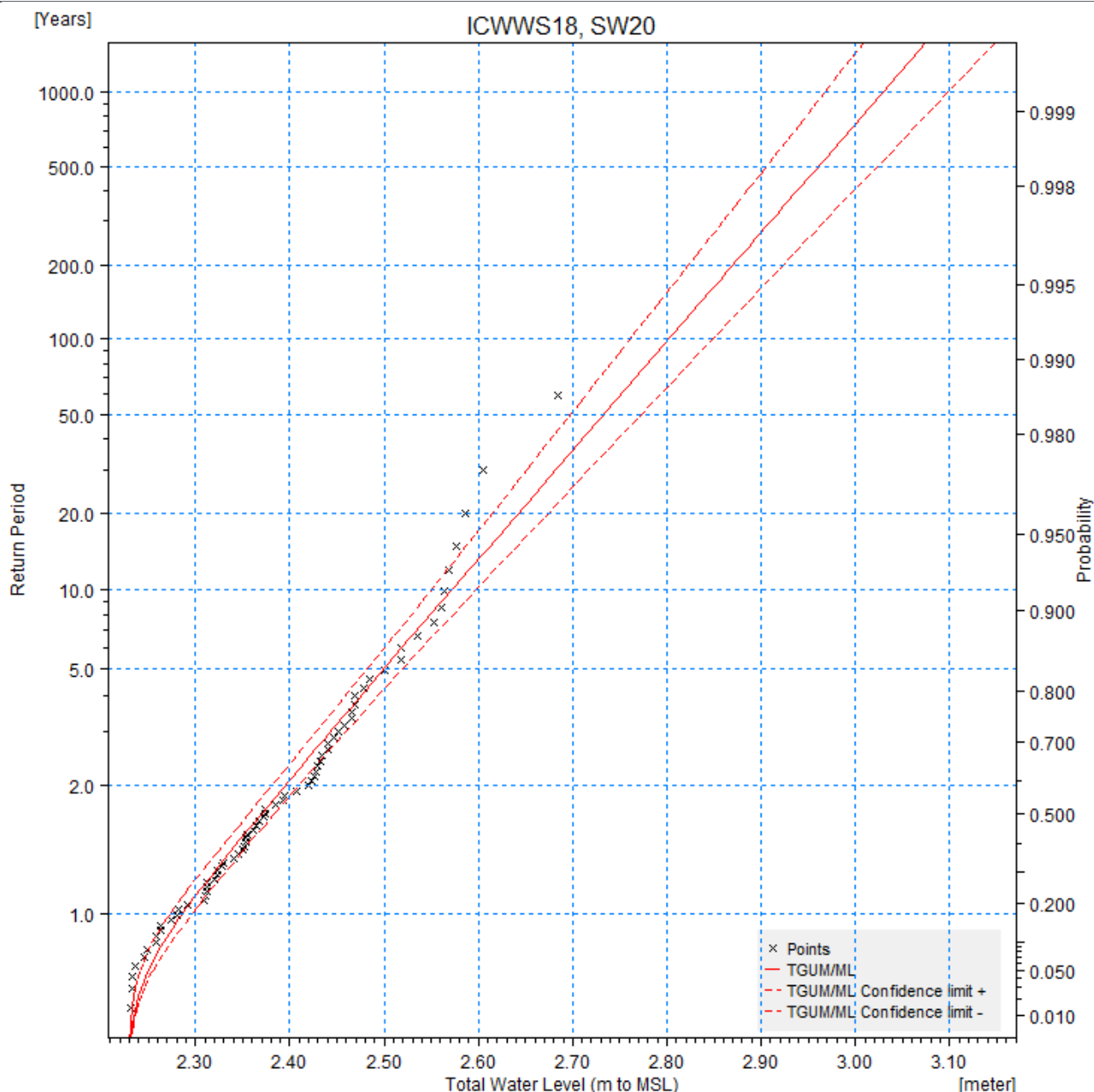


Figure 6.1: Sample Extreme Value Analysis plot for South West coast Total Water Level

All EVA results are presented in Appendices D to I, as listed below.

Coastal Assessment Area	Appendix
North East Coast, including Carlingford Lough	D
South East Coast, including Wexford Harbour	E
South Coast, including Waterford Estuary and Cork Harbour	F
South West Coast, including Shannon Estuary	G
West Coast	H
North West Coast	I

6.3 Extreme Value Analysis of Surge Residual

An extreme value analysis of surge residual was undertaken as described in Section 6.1 for the majority of the estimation points on the North East and South East coasts (for estimation points NE1-3, NE7-16, NE18-26, SE1-30, SE35-40).

The best fit results were obtained by using the threshold or fixed location parameter method for selecting data. The most successful candidate distributions and respective method used to evaluate the parameters are given in Table 6.2 for each relevant section of coastline:

Table 6.2: Best fitting Distributions of Surge Residual for relevant Coastal Areas

Coastal Assessment Area	Distribution	Method
North East Coast	Truncated Gumbel	Maximum Likelihood
South East Coast	Truncated Gumbel	Maximum Likelihood

The extreme water levels were evaluated for return periods ranging from less than 1 year to 1 in 1000 year. A sample extreme value analysis plot is shown in Figure 6.2, illustrating the Truncated Gumbel Maximum Likelihood method best fit estimation of probability distribution.

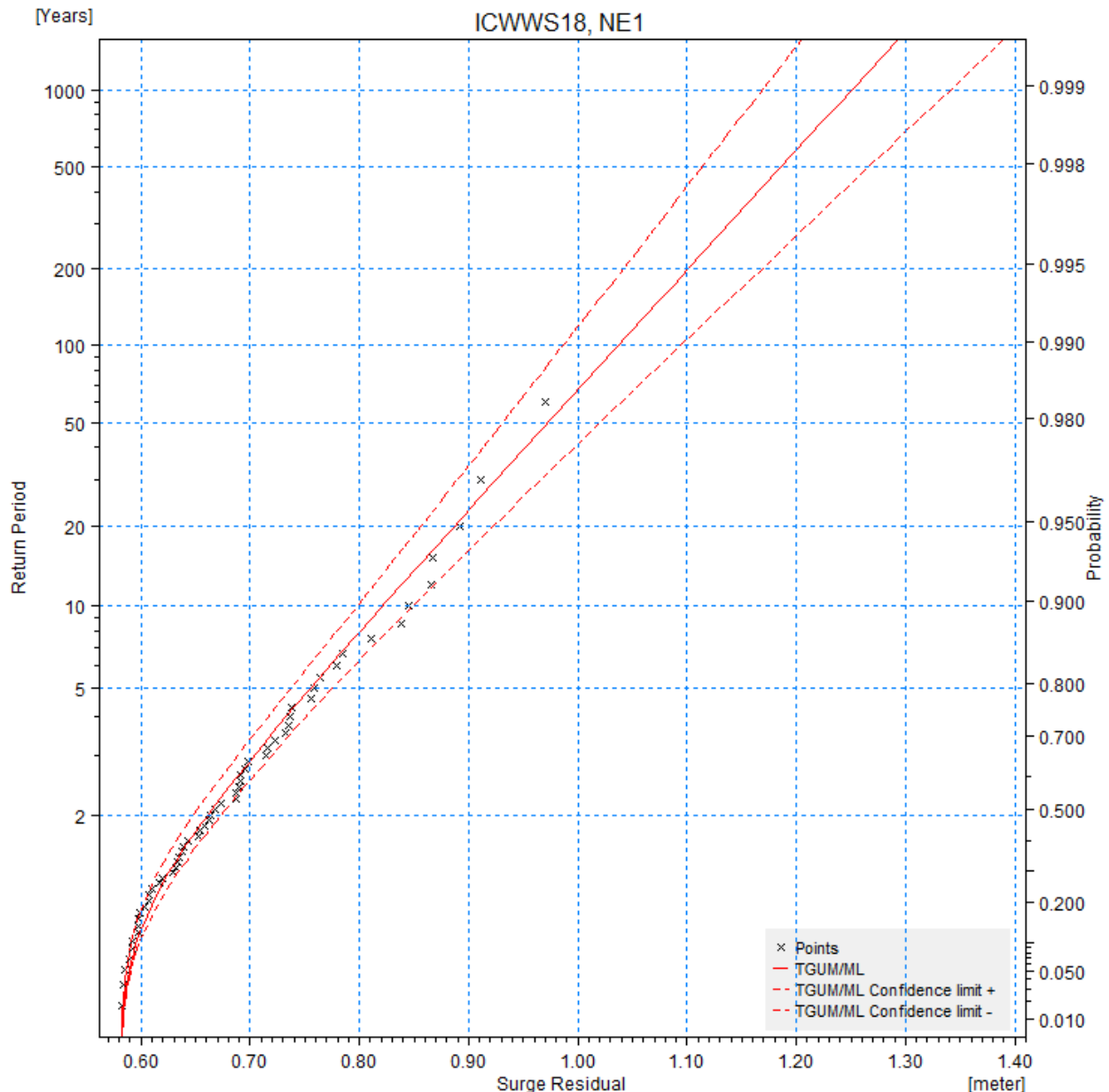


Figure 6.2: Sample Extreme Value Analysis plot for North East coast Surge Residual

All EVA results can be found in Appendices D and E, as listed below.

Coastal Assessment Area	Appendix
North East Coast	D
South East Coast	E

6.4 Extreme Value Analysis of Astronomic Tides

In order to derive extreme water levels for the North East and South East coasts appropriate astronomical tidal conditions were required for combination with the extreme surge residuals identified through the process described in the preceding section. Even though the occurrence of certain tidal levels is not a random process but determined by the reoccurring constellation of sun and moon in relation to the earth, the joint occurrence of a certain tidal level and a specific surge level can be considered semi-random. Thus the extreme tidal levels

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on the North East and South East coasts were also analysed using an extreme value analysis, as part of the ICPSS. These extreme tides were subsequently used in the joint probability analysis described in the following section. Details on the derivation of extreme tides can be found in the ICPSS reports for the South East and North East coasts (References 1 and 2).

6.5 Joint Probability Analysis of Tidal and Storm Surge Water Levels

Joint probability analysis of tides and surge was undertaken for the majority of the North East and South East coast estimation points, 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 9). This method involves selecting a correlation coefficient between each pair of variables. Correlation coefficients were derived as part of the ICPSS and remained the same for the current study. For more details on their derivation, refer to the ICPSS South East and North East reports (References 1 and 2).

With the appropriate correlation coefficient selected, the relevant set of return period surge residuals and astronomic tides were input into the JOIN-SEA spreadsheet for analysis. This yielded a table of the return period of the tidal element against the return period of the surge element for a range of joint probability events. From these tables, the appropriate surge and tidal level combinations were identified for creation of the relevant extreme water levels. Up to thirteen water levels were calculated as a result of the joint probability analysis, with the highest water level taken as the extreme water level for each point and return period event. The joint probability results for the North East and South East coasts can be found in Appendix J and K respectively.

In general the extreme water levels were found to be associated with higher return period surges and relatively low return period tidal levels, though this varied throughout the North East and South East Coasts.

6.6 Dundalk Bay and Portmarnock

Given the nature of the coastline north of Howth and in Dundalk Bay, some of the extreme value points selected in the model had to be placed in drying areas to be sufficiently close to the coast. This made it difficult to calculate valid surge residual values, as during storm periods, the drying banks become flooded. This resulted in large surge residuals which, however, would not immediately lead to flooding above the high water mark. Secondly, the flooding and drying in this area can cause locally high flow velocities, which can affect the build-up of extreme storm surge levels.

In order to derive return period water levels, the total water levels at these drying locations were compared to total water levels at a nearby deep water estimation point. Four of the original 26 estimation points were analysed as described above in order to compute corresponding water levels, using the same relationships identified during the ICPSS. These estimation points included NE4, NE5, NE6 and NE17. See Reference 2 for further details on these correlations.

7 SEICHING ANALYSIS

The results of the basic surge modelling did not demonstrate any seiching effects or local wind set-up in the bays and estuaries, however seiching/local wind set-up effects generally cannot be simulated using the 3 hourly met dataset. This is principally due to the lack of any information on gust speeds or variation in wind speeds due to gusts within the three hourly datasets.

During the ICPSS, simulations with pseudo random variation of wind speed and direction were carried out to derive an estimate of typical seiching/local wind set-up amplitude, at each estimation point. The seiching/local wind set up allowance for the estimation points in each ICWWS 2018 coastal assessment area is listed in Table 7.1 to Table 7.11, which mirror the ICPSS values. These values were added to the total water levels derived from the extreme value analysis, to provide the final estimated extreme water levels at all estimation points around the coast of Ireland, as discussed in Section 8.

Table 7.1: Seiching/ Local wind set-up allowance for each point on the North East coast

NE1	0.05	NE14	0.05
NE2	0.05	NE15	0.10
NE3	0.10	NE16	0.10
NE4	0.10	NE17	0.10
NE5	0.10	NE18	0.05
NE6	0.10	NE19	0.15
NE7	0.05	NE20	0.15
NE8	0.05	NE21	0.20
NE9	0.10	NE22	0.20
NE10	0.10	NE23	0.15
NE11	0.10	NE24	0.10
NE12	0.05	NE25	0.10
NE13	0.05	NE26	0.10

Table 7.2: Seiching/ Local wind set-up allowance for each point in Carlingford Lough

NE27	0.10
NE28	0.10
NE29	0.10

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Table 7.3: Seiching/ Local wind set-up allowance for each point on the South East coast

SE1	0.05	SE19	0.05
SE2	0.10	SE20	0.05
SE3	0.05	SE21	0.05
SE4	0.05	SE22	0.05
SE5	0.05	SE23	0.05
SE6	0.05	SE24	0.05
SE7	0.05	SE25	0.05
SE8	0.05	SE26	0.05
SE9	0.05	SE27	0.05
SE10	0.05	SE28	0.05
SE11	0.05	SE29	0.05
SE12	0.05	SE30	0.05
SE13	0.05	SE35	0.05
SE14	0.05	SE36	0.05
SE15	0.05	SE37	0.05
SE16	0.05	SE38	0.05
SE17	0.05	SE39	0.05
SE18	0.05	SE40	0.05

Table 7.4: Seiching/ Local wind set-up allowance for each point in Wexford Harbour

SE31	0.05
SE31b	0.10
SE32	0.10
SE33	0.10
SE33b	0.10
SE34	0.10

Table 7.5: Seiching/ Local wind set-up allowance for each point on the South coast

S1	0.10	S25	0.10
S2	0.10	S26	0.10
S3	0.10	S27	0.10
S4	0.15	S28	0.10
S5	0.25	S29	0.10
S6	0.20	S30	0.15
S7	0.10	S31	0.15
S8	0.20	S32	0.10
S9	0.20	S33	0.10
S10	0.10	S34	0.10
S11	0.10	S35	0.15
S12	0.10	S36	0.10
S13	0.10	S37	0.10
S14	0.10	S38	0.10
S15	0.10	S39	0.10
S16	0.10	S40	0.10
S17	0.10	S41	0.10
S18	0.10	S42	0.15
S19	0.10	S43	0.20
S20	0.10	S44	0.20
S21	0.10	S45	0.15
S22	0.10	S46	0.10
S23	0.10	S47	0.10
S24	0.10	S48	0.10

Table 7.6: Seiching/ Local wind set-up allowance for each point in Cork Harbour

C1	0.10
C2	0.15
C3	0.20
C4	0.15
C5	0.15
C6	0.10

Table 7.7: Seiching/ Local wind set-up allowance for each point in Waterford Harbour

W1	0.10
W2	0.10
W3	0.10
W4	0.10
W5	0.10

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Table 7.8: Seiching/ Local wind set-up allowance for each point on the South West coast

SW1	0.05	SW21	0.05	SW41	0.05
SW2	0.05	SW22	0.05	SW42	0.05
SW3	0.05	SW23	0.05	SW43	0.05
SW4	0.05	SW24	0.05	SW44	0.05
SW5	0.05	SW25	0.05	SW45	0.05
SW6	0.05	SW26	0.05	SW46	0.05
SW7	0.10	SW27	0.05	SW47	0.05
SW8	0.10	SW28	0.05	SW48	0.05
SW9	0.05	SW29	0.05	SW49	0.05
SW10	0.05	SW30	0.05	SW50	0.05
SW11	0.05	SW31	0.05	SW51	0.05
SW12	0.05	SW32	0.05	SW52	0.05
SW13	0.05	SW33	0.05	SW53	0.05
SW14	0.05	SW34	0.10	SW54	0.05
SW15	0.05	SW35	0.10	SW55	0.05
SW16	0.05	SW36	0.10	SW56	0.05
SW17	0.05	SW37	0.10	SW57	0.10
SW18	0.05	SW38	0.05	SW58	0.10
SW19	0.10	SW39	0.05		
SW20	0.10	SW40	0.05		

Table 7.9: Seiching/ Local wind set-up allowance for each point in the Shannon Estuary

S1	0.05	S14	0.10
S2	0.10	S15	0.05
S3	0.10	S16	0.05
S4	0.10	S17	0.05
S5	0.10	S18	0.05
S6	0.10	S19	0.05
S7	0.10	S20	0.05
S8	0.10	S21	0.10
S9	0.15	S22	0.10
S10	0.10	S23	0.10
S11	0.10	S24	0.10
S12	0.10	S25	0.10
S13	0.10	S26	0.15

Table 7.10: Seiching/ Local wind set-up allowance for each point on the West coast

W1	0.15	W25	0.05	W49	0.05
W2	0.10	W26	0.05	W50	0.05
W3	0.25	W27	0.05	W51	0.05
W4	0.15	W28	0.05	W52	0.05
W5	0.15	W29	0.05	W53	0.05
W6	0.15	W30	0.05	W54	0.05
W7	0.15	W31	0.05	W55	0.05
W8	0.10	W32	0.05	W56	0.05
W9	0.10	W33	0.05	W57	0.10
W10	0.05	W34	0.05	W58	0.05
W11	0.05	W35	0.05	W59	0.05
W12	0.05	W36	0.05	W60	0.00
W13	0.05	W37	0.05	W61	0.05
W14	0.05	W38	0.05	W62	0.00
W15	0.05	W39	0.10	W63	0.00
W16	0.05	W40	0.10	W64	0.00
W17	0.05	W41	0.10	W65	0.05
W18	0.05	W42	0.15	W66	0.00
W19	0.05	W43	0.10	W67	0.05
W20	0.05	W44	0.10	W68	0.05
W21	0.05	W45	0.05	W69	0.05
W22	0.05	W46	0.05	W70	0.05
W23	0.05	W47	0.05	W71	0.05
W24	0.05	W48	0.05		

Table 7.11: Seiching/ Local wind set-up allowance for each point on the North West coast

NW1	0.05	NW19	0.00	NW37	0.00
NW2	0.05	NW20	0.00	NW38	0.00
NW3	0.05	NW21	0.00	NW39	0.00
NW4	0.05	NW22	0.00	NW40	0.00
NW5	0.05	NW23	0.05	NW41	0.05
NW6	0.05	NW24	0.00	NW42	0.00
NW7	0.05	NW25	0.00	NW43	0.05
NW8	0.05	NW26	0.00	NW44	0.00
NW9	0.05	NW27	0.00	NW45	0.00
NW10	0.05	NW28	0.00	NW46	0.00
NW11	0.05	NW29	0.00	NW47	0.00
NW12	0.05	NW30	0.00	NW48	0.00
NW13	0.05	NW31	0.00	NW49	0.00
NW14	0.05	NW32	0.00	NW50	0.00
NW15	0.05	NW33	0.00	NW51	0.00
NW16	0.05	NW34	0.00	NW52	0.00
NW17	0.05	NW35	0.00		
NW18	0.00	NW36	0.05		

8 RESULTS AND STUDY OUTPUT

The extreme water levels derived as part of this study were compared with the corresponding levels produced as part of the ICPSS at each of the estimation points. This comparison was initially made using water levels produced to MSL, with a second comparison using water levels to OD Malin (OSGM02) for consistency with the ICPSS.

The comparison made using MSL values revealed increases or decreases in the ICWWS 2018 water levels, due to the availability of additional bathymetry and meteorological data and the subsequent updated modelling and statistical analysis. In the majority of cases, the extreme water levels to MSL had increased for most of the AEPs since the previous study, reflecting the ongoing trend of increased storminess in recent years. However, there were a number of estimation points which produced marginally lower results when compared to the ICPSS. Any reductions indicated in the ICWWS 2018 were generally considered to be within the accuracy of the modelling techniques employed, apart from the reductions indicated for the points situated in the upper Shannon Estuary (east of estimation point S13).

Due to the statistical methods employed within the Extreme Value Analysis, the extreme water levels, particularly for the less frequent events, are sensitive to the type and shape of the chosen distributions and thresholds. Therefore, for two independent sets of results, i.e. for the ICPSS and the ICWWS 2018, differences were not unexpected and were generally within the anticipated tolerances. For example, on the South West coast, the ICPSS found the Truncated Gumbel the best fitting distribution at all estimation points, whereas the ICWWS 2018 deemed the Truncated Gumbel, along with the two parameter Weibull and Gamma as the best fitting distributions. Similarly, for the North East Coast, the ICPSS used the two parameter Weibull distribution at all estimation points, whereas the ICWWS 2018 used the Truncated Gumbel. Furthermore, at some of the estimation points, the same largest modelled event occurred in both the ICWWS 2018 and ICPSS datasets, with the ICPSS having a reduced record length by up to 10 years in comparison with the ICWWS 2018. As such, where the ICWWS 2018 record length was 60 years, compared with 50 years for the ICPSS, the same maximum event would be assigned as a 1 in 60 year event, compared to a 1 in 50 year event in the ICPSS. If the extreme events in the ICWWS 2018 are not large enough in magnitude or frequency, then the dominance of the one peak event will hold, and the results will likely be lower than the ICPSS. However, this is likely to reflect a slight over-prediction of the ICPSS results, rather than an under prediction of the ICWWS 2018 results, as with each additional year of data accounted for in the assessment, the confidence in the results of statistical analysis improves. Furthermore, in a number of locations, the South West and North West coasts, the Shannon Estuary and Carlingford Lough, all models were updated with the most recent and relevant bathymetry available and all events re-simulated. Thus, the confidence in the ICWWS 2018 results has greatly improved from the ICPSS.

Figure 8.1 shows graphically whether there has been an increase, decrease or no change in the results to MSL between the ICPSS and the ICWWS 2018, when comparing the 0.5% AEP event at each estimation point. The areas where the ICWWS 2018 0.5% AEP results showed an increase in estimated extreme water levels compared with the ICPSS are shown in green; those areas where the water levels decreased are shown in red and the small number of cases where the result was the same are shown in blue.

Legend**ICWWS 2018 / ICPSS Estimation Points**

- Decrease
- Increase
- Same

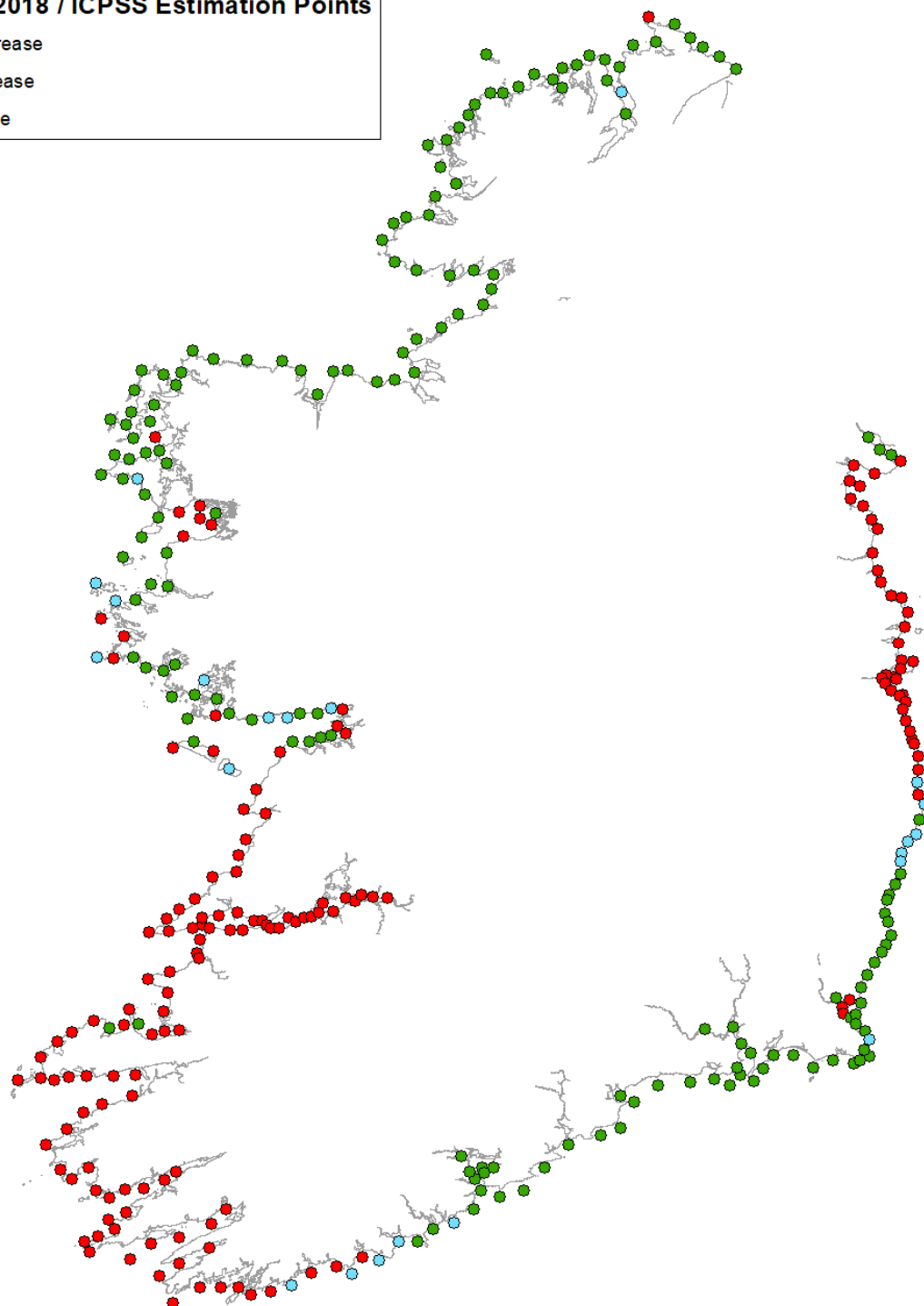


Figure 8.1: Comparison between ICWWS 2018 and ICPSS estimated extreme water levels at Estimation Points to Mean Sea Level

The North East coast showed a reduction in extreme water levels, most likely due to its relatively sheltered location in the Irish Sea, where the impact of increased storm surges are not as evident as on much of the Atlantic coastline. The same applied to the northern parts of the South East coast, whereas for the southern parts of the South East coast (Wicklow Head to Carnsore Point, including Wexford Harbour), the effect of

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increased storminess has resulted in increased estimated extreme water levels. Carlingford Lough also yielded an increase in water levels. This is likely to be due to the inclusion of all identified events on the north east coast in the ICWWS 2018, whereas these events were filtered in the ICPSS, and only a selection of the north east events were simulated for Carlingford Lough.

The eastern part of the south coast, from Carnsore Point to Courtmacsherry (including Waterford Estuary and Cork Harbour) was subject to increased water levels, whilst from Courtmacsherry to Bantry Bay, no increase was evident. As per the ICPSS, it was determined that Points S46 to S48 water levels were more reliably represented using an adjustment taken from the South East coast analysis.

With regard to the South West coast, the majority of estimation points did not show any increase in water level, although on the approach to the West coast in Galway Bay, an increase became apparent, in line with the findings of the West and North West coasts which also showed an increase in the majority of locations.

In the case of the Shannon Estuary, the updated analysis indicated a significant reduction in extreme water levels since the ICPSS, at circa 0.6m to 0.9m to MSL in the upper Shannon Estuary east of estimation point S21, with moderate reductions between estimation points S13 and S21. However, due to the uncertainties of the ICPSS modelling in this area, as described in Section 5.3, a significant difference in the results was not unexpected.

A comparison between the ICWWS 2018 and ICPSS estimated extreme water levels was also made using the OD Malin (OSGM02) output values to indicate increases or decreases in the ICWWS 2018 water levels, due to the availability of additional bathymetry and meteorological data and the subsequent updated modelling and statistical analysis, and also the conversion from MSL to OD Malin (OSGM02). Figure 8.2 shows a comparison plot of the changes between the two sets of results to OD Malin (OSGM02) when reviewing AEPs from 50% to 0.1%. Those points where all ICWWS 2018 AEP water levels have increased since the ICPSS are shown in green, with decreases shown in red. Those points where there are both increases and decreases depending on the AEP are shown in blue. For the majority of the points, there has been an uplift in the ICWWS 2018 extreme water levels to OD Malin (OSGM02) compared with the ICPSS. Similarly to Figure 8.1, it is the north east and south east coasts, along with the Shannon Estuary, where decreases at some or all of the AEPs are apparent. However, these decreases are fewer and less widespread than in Figure 8.1, which emphasises the effect the improvement in the MSL to OD Malin conversions has had on the results.

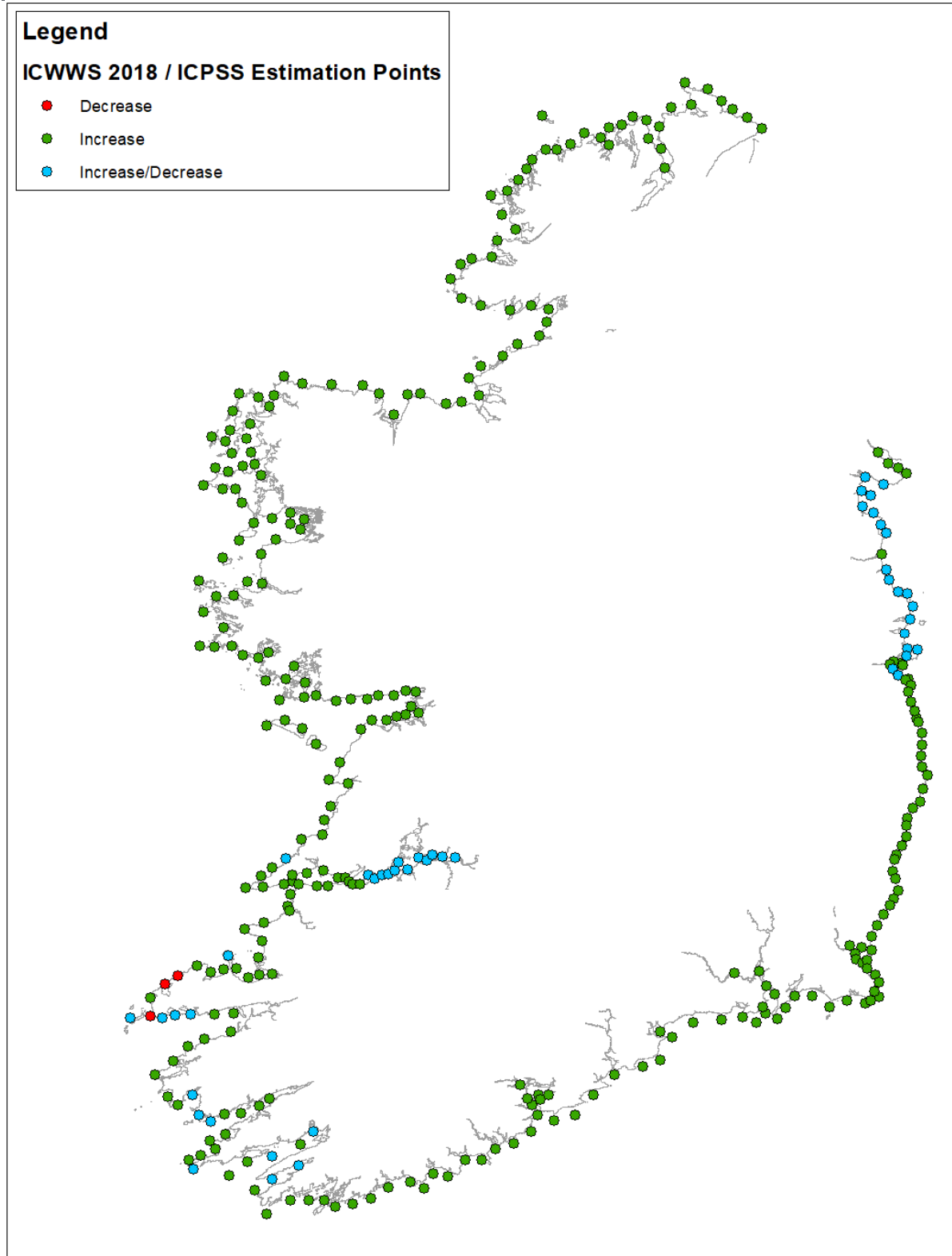


Figure 8.2: Comparison between ICWWS 2018 and ICPSS estimated extreme water levels at Estimation Points to OD Malin (OSGM02)

A full comparison of the ICWWS 2018 and ICPSS estimated extreme water levels for all AEPs at each estimation point to OD Malin (OSGM02) can be found in Appendix L. These values include the addition of the relevant seiche or local wind set-up values, as discussed in Section 7.

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The complete suite of ICWWS 2018 Phase 1 estimated extreme water level results for the Present Day Scenario are produced to Mean Sea Level (MSL), OD Malin (OSGM02) and OD Malin (OSGM15) and are located in Appendix M. A sample results table is shown in Table 8.1 for Points NE1 to NE10 on the North East coast. The results tables also include the seiching / local wind set-up applied to each estimation point, along with the relevant OD Malin (OSGM02) and OD Malin (OSGM15) conversions derived during Phase 4. Similarly, estimated extreme water level results for the Mid-Range Future Scenario, High End Future Scenario, High+ End Future Scenario and the High++ End Future Scenario are located in Appendices N, O, P and Q respectively. The MSL to OD Malin conversions shown in Table 8.1 and Appendices L to Q are the corrections applied to the extreme water levels to adjust the datum from MSL to OD Malin i.e. a positive correction indicates that MSL is above OD Malin, and a negative value indicates that MSL is below OD Malin.

Table 8.1: Sample seiching/ local wind set-up adjustment and water levels to MSL, OD Malin (OSGM02) and OD Malin (OSGM15) for North East coast (NE1 to NE10)

		NE1	NE2	NE3	NE4	NE5	NE6	NE7	NE8	NE9	NE10
Coord- inate	Longitude	-6.082	-6.221	-6.326	-6.354	-6.348	-6.284	-6.241	-6.212	-6.240	-6.219
	Latitude	54.012	53.976	54.005	53.956	53.900	53.879	53.838	53.806	53.732	53.680
Water Level - metres to MSL	50%	3.07	3.10	3.23	3.15	3.09	3.05	2.99	2.95	2.93	2.92
	20%	3.17	3.19	3.31	3.24	3.18	3.14	3.08	3.06	3.03	3.01
	10%	3.24	3.26	3.38	3.30	3.25	3.21	3.16	3.14	3.10	3.08
	5%	3.31	3.33	3.44	3.37	3.32	3.28	3.23	3.22	3.18	3.15
	2%	3.41	3.42	3.52	3.46	3.41	3.38	3.33	3.32	3.27	3.24
	1.00%	3.49	3.49	3.59	3.52	3.48	3.45	3.40	3.40	3.34	3.31
	0.50%	3.56	3.56	3.65	3.59	3.55	3.52	3.48	3.48	3.42	3.38
	0.10%	3.73	3.72	3.80	3.74	3.71	3.69	3.65	3.67	3.59	3.54
seich / set-up allowance		0.05	0.05	0.10	0.10	0.10	0.10	0.05	0.05	0.10	0.10
Water Level - metres to MSL (including seiche/set-up)	50%	3.12	3.15	3.33	3.25	3.19	3.15	3.04	3.00	3.03	3.02
	20%	3.22	3.24	3.41	3.34	3.28	3.24	3.13	3.11	3.13	3.11
	10%	3.29	3.31	3.48	3.40	3.35	3.31	3.21	3.19	3.20	3.18
	5%	3.36	3.38	3.54	3.47	3.42	3.38	3.28	3.27	3.28	3.25
	2%	3.46	3.47	3.62	3.56	3.51	3.48	3.38	3.37	3.37	3.34
	1.00%	3.54	3.54	3.69	3.62	3.58	3.55	3.45	3.45	3.44	3.41
	0.50%	3.61	3.61	3.75	3.69	3.65	3.62	3.53	3.53	3.52	3.48
	0.10%	3.78	3.77	3.90	3.84	3.81	3.79	3.70	3.72	3.69	3.64
MSL to OD Malin (OSGM02)		0.17	0.02	-0.05	-0.04	-0.04	-0.04	-0.03	-0.03	0.07	-0.03
Water Level - metres to OD Malin (OSGM02) (including seiche/set-up)	50%	3.29	3.17	3.28	3.21	3.15	3.11	3.01	2.97	3.10	2.99
	20%	3.39	3.26	3.36	3.30	3.24	3.20	3.10	3.08	3.20	3.08
	10%	3.46	3.33	3.43	3.36	3.31	3.27	3.18	3.16	3.27	3.15
	5%	3.53	3.40	3.49	3.43	3.38	3.34	3.25	3.24	3.35	3.22
	2%	3.63	3.49	3.57	3.52	3.47	3.44	3.35	3.34	3.44	3.31
	1.00%	3.71	3.56	3.64	3.58	3.54	3.51	3.42	3.42	3.51	3.38
	0.50%	3.78	3.63	3.70	3.65	3.61	3.58	3.50	3.50	3.59	3.45
	0.10%	3.95	3.79	3.85	3.80	3.77	3.75	3.67	3.69	3.76	3.61
MSL to OD Malin (OSGM15)		0.18	0.02	-0.05	-0.05	-0.05	-0.05	-0.03	-0.03	0.07	-0.03
Water Level - metres to OD Malin (OSGM15) (including seiche/set- up)	50%	3.30	3.17	3.28	3.20	3.14	3.10	3.01	2.97	3.10	2.99
	20%	3.40	3.26	3.36	3.29	3.23	3.19	3.10	3.08	3.20	3.08
	10%	3.47	3.33	3.43	3.35	3.30	3.26	3.18	3.16	3.27	3.15
	5%	3.54	3.40	3.49	3.42	3.37	3.33	3.25	3.24	3.35	3.22
	2%	3.64	3.49	3.57	3.51	3.46	3.43	3.35	3.34	3.44	3.31
	1.00%	3.72	3.56	3.64	3.57	3.53	3.50	3.42	3.42	3.51	3.38
	0.50%	3.79	3.63	3.70	3.64	3.60	3.57	3.50	3.50	3.59	3.45
	0.10%	3.96	3.79	3.85	3.79	3.76	3.74	3.67	3.69	3.76	3.61

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The conclusions of Phase 1 of the Irish Coastal Wave and Water Level Modelling Study 2018 are as follows:-

1. The inclusion of additional years of meteorological data compared to the ICPSS, has resulted in evidence of an increase in storminess at a majority of estimation points around the coast of Ireland. However due to the frequency and magnitude of the increased storms at some locations, this did not necessarily result in an increase at the more extreme AEP events. In cases where an increase in the frequency of recent extreme events was noted, but the magnitude did not exceed those events modelled during the ICPSS, this generally led to a change in the slope of the statistical distribution, where the more extreme AEP water levels decreased and the less extreme AEP water levels increased compared with the ICPSS. For example, where the ICWWS 2018 record length was 60 years, compared with 50 years for the ICPSS, the same maximum event would be assigned as a 1 in 60 year event, compared to a 1 in 50 year event in the ICPSS. Therefore the more extreme AEP events would decrease, however the less extreme AEP events would increase due to an increased frequency in extreme events within the dataset. This generally resulted in the shape of the best fitting statistical distribution being broadly similar to the ICPSS, with a change in slope of the curve reflecting the change in magnitude and frequency of events. This is likely to reflect a slight over-prediction of the ICPSS results, rather than an under prediction of the ICWWS 2018 results.
2. The approach of combining synthesised data from the Irish Seas Tidal Surge Model (ISTSM) with available tide gauge data and undertaking joint probability analysis to derive extreme water levels around the coastline was applied to the majority of the south east and north east coast estimation points due to the complex Irish Sea location. An extreme value analysis of total water levels was carried out for the south and western Atlantic coasts, with no requirement for joint probability analysis.
3. The improvement in the modelling and statistical analysis due to the availability of additional bathymetry and meteorological data resulted in increased confidence in the ICWWS 2018 results in comparison with the ICPSS results, with the model tolerance for estimated extreme water levels being reduced from $\pm 180\text{mm}$ to $\pm 150\text{mm}$ relative to OD Malin (OSGM15). The model validation undertaken in this study showed that relatively narrow tolerances were achieved using the applied methodology and thus the extreme water levels derived are considered to be of sufficient accuracy not only for this strategic level study but also potentially for more detailed investigations (depending on their scope and accuracy requirements). The estimated accuracy of the total water levels presented in this report are within $\pm 150\text{mm}$ relative to OD Malin (OSGM15) for all estimation points around the coast of Ireland.
4. At the majority of estimation points, there was an increase in the ICWWS 2018 extreme water levels to OD Malin (OSGM02) compared with the ICPSS. The upper Shannon Estuary estimation points did however show a marked decrease in extreme water levels for the more extreme events. This significant change was the result of improved availability of bathymetric and tide gauge data for the ICWWS 2018.
5. Whilst every effort has been taken throughout this study to optimise the accuracy of the estimated extreme water levels produced, there are unavoidable inaccuracies and uncertainties associated with these levels. These uncertainties are discussed and highlighted throughout the report and include uncertainties in topographic and other survey data, inaccuracy in meteorological data, assumptions and / or approximations in tidal boundary 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, including assumptions and / or approximations relating to tide gauge data.

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6. Although, the network of tide gauge data has vastly improved since the ICPSS, there are still limitations in the derivation of the MSL to OD Malin (OSGM15) surface as discussed under Phase 4 due to the lack of long term tide gauge records in certain areas, for example the Shannon Estuary, south east and western coasts. This is also considered a limitation for the estimation of the Phase 1 extreme water levels.

9.2 Recommendations

The recommendations of this study are as follows:-

1. The OPW has improved and expanded their tide gauge network in Ireland since the ICPSS, however there are still a number of areas where long term records are lacking or gauges do not exist. To further refine the MSL to OD Malin (OSGM15) conversion and to provide improved model validation/ calibration data in the future, it is recommended that the OPW expands and maintains their network of tide gauges in Ireland. In line with Phase 4 recommendations, consideration should be given to deploying additional tide gauges along the south east coast, and the Cork/Kerry, Clare, Galway/Mayo coastlines.
2. Uncertainty in the performance of the Shannon Estuary model in replicating the propagation of surges on high tides to the upper Shannon Estuary, may be reduced by improving the performance of the available tide gauges during extreme events. This might potentially involve the deployment of an additional tide gauge in the vicinity of Limerick. The collection of further bathymetric data in the upper reaches of the Shannon would also be beneficial. The recent installation of a gauge at Shannon airport will provide valuable validation data in future.
3. It is recommended that a review of the MSL to OD Malin (OSGM15) relationship be undertaken following collation of two to three years of data for those gauges where less than one year was available at the time of this study.
4. The extreme water level outputs of Phase 1 of the ICWWS 2018 may be enhanced in the future, following the acquisition of additional years of storm events for analysis. As such, it is recommended that the study be updated at regular intervals (e.g. 6 years), incorporating the most recent identified storms to improve the statistical analysis, whilst also improving the MSL to OD Malin (OSGM15) conversion due to an increasing number of longer tide gauge records around the country.

10 REFERENCES

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Reference 3: RPS Consulting Engineers, June 2010, Final Technical Report “ICPSS, Phase 3, Work Packages 2, 3 & 4A, Strategic Assessment of Coastal Flooding and Erosion Extents – South Coast - Carnsore Point to Bantry Bay”

Reference 4: RPS, December 2013, Technical Report “ICPSS – Phase IV, Work Packages 2, 3 & 4A, Strategic Assessment of Coastal Flooding and Erosion Extents – South West Coast - Bantry Bay to Ballyvaghan Bay”

Reference 5: RPS, August 2014, Technical Report “ICPSS – Phase IV, Work Packages 2, 3 & 4A, Strategic Assessment of Coastal Flooding and Erosion Extents – West Coast - Ballyvaghan Bay to Killala Bay”

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Reference 7: RPS Consulting Engineers, January 2006: “Calibration of tidal surge model with astronomic tides”

Reference 8: RPS, April 2018: “Tidal and Storm Surge Forecasting Services for the Coast of Ireland – Period 10 (2017/2018): Evaluation and Forecast Accuracy Assessment Interim Report”

Reference 9: DEFRA / Environment Agency, March 2005, R&D Technical Report FD2308/TR2, “Use of Joint Probability Methods in Flood Management: A Guide to Best Practice”

11 GLOSSARY OF TERMS

ADI	Alternating Direction Implicit – finite difference method used in numerical analysis
Admiralty data	Bathymetry data extracted via C-Map representing Admiralty Charts produced by the United Kingdom Hydrographic Office.
AEP	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.
Astronomic tides	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.
Bathymetry	Data giving the depth of a large water body to provide the underwater topography.
Chi-Square	A statistical calculation that tests the goodness of fit of observed values compared to theoretical probability, and determines whether it is likely to occur by chance or is atypical. i.e. the greater difference between observed and expected frequencies, the more likely it is statistically significant.
C-Map	Part of the MIKE Suite of Software, enabling bathymetry data to be extracted for modelling purposes.
Confidence Limits	Two statistics that form the upper and lower bounds of a confidence interval and predict the range of values within which a particular parameter lies. For example, the 95% confidence limits would encase 95% of the data between two boundaries, with 2.5% of the overall data removed at either end.
Coriolis Acceleration	The acceleration experienced by a mass moving in a north south direction due to the Earth's rotation.
Correlation Coefficients	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.
Datum (geographic)	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.
DEFRA	Department for Environment, Food and Rural Affairs

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Dfs2	Marine GIS two dimensional grids used as part of the MIKE Suite of Software, often used to display hydrodynamic data, for example model results or input climatic conditions or bathymetry.
DTU10	Global Mean Sea Surface model as produced by the Danish National Space Institute
ECMWF	European Centre for Medium Range Weather Forecasts: International meteorological organisation funded by large number of European national meteorological services.
ERA 5	Created by ECMWF, the ERA 5 dataset contains a large amount of reanalysis climate data for years 1950-present.
EVA	Extreme Value Analysis: A statistical analysis of stochastic processes to estimate the probabilities of rare or extreme events.
Gamma distribution	A two parameter family of continuous probability distribution.
Generalised Pareto distribution	A right-skewed probability distribution law that can model tails of a wide variety of distributions.
GSI	Geological Survey Ireland: provide information and data on aspects of Irish geology.
ICPSS	Irish Coastal Protection Strategy Study
ICWWS	Irish Coastal Wave and Water Level Modelling Study
INFOMAR	Surveying programme managed by GSI and Marine Institute with the aim of surveying and mapping most of the offshore Irish seabed.
ISTSM	Irish Seas Tidal Surge Model
Jack-knife Resampling Technique	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.

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Joint Probability Analysis	Analysis to derive the probability of occurrence of events in which two or more specific outcomes will simultaneously occur.
Kolmogorov-Smirnov Test	Often referred to as the K-S test, it tests the goodness of fit between the expected distribution and the observed distribution.
LiDAR data	Light Detection and Ranging: Uses light signals through lasers and optical detectors to measure land elevation.
Log-Normal distribution	A probability distribution whereby the log of the random variable is normally distributed
Log-Pearson Type3 distribution	A probability distribution whereby the log of the random variable follows the Pearson distribution. A statistical technique that typically predicts the flood of a river and calculates the distribution frequency, so floods of various sizes can be predicted.
Marine Institute	Coordinates marine research and development in Ireland, including the management of a system of tide gauges around the coastline.
Maximum Likelihood Method	A technique in statistics in which the parameters are determined that maximise the fit between the probability distribution and the sample data
MEDIN	Marine Environmental Data and Information Network – partnership of UK organisations improving access to UK marine data
Method of L-moments	Linear combinations of probability weighted moments that provide measures of location, dispersion, skewness, and shape of the data sample.
Method of Moments	A technique for constructing estimated parameters that are based on matching the sample moments with the corresponding distribution moments.
MIKE 21 flexible mesh	Two dimensional flexible mesh coastal modelling package produced by DHI (The Danish Hydraulic Institute)
MSL	Mean Sea Level: the average sea surface level of all tides over a long period of time.
O.D. Malin	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

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OPW	Office of Public Works
OSGM02	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
OSGM15	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
OSi	Ordnance Survey Ireland is the National Mapping Agency for Republic of Ireland.
Partial Duration Series (PDS)	PDS is also known as peak over threshold (POT) series and analyses extreme events whereby data above a threshold is used independently of its occurrence in the record (in contrast to an Annual Maximum Series).
Seiche	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.
Standard Deviation	A statistical measure of the spread of data from the mean.
Standardised Least Squares Criterion	A method of fitting a distribution to a fixed collection of points using the square of the difference between the observed data and the calculated data point.
Surge	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.
Surge Residual	The change in sea level caused by the effect of pressure variations and persistently strong winds.
Theoretical Probability Distributions	A statistical function that describes all possible values and likelihoods that a random variable can take within a given range.
Threshold/Fixed Location Parameter Method	Method of fixing the “origin” of a probability distribution by using the threshold from the POT analysis
Tidal Harmonics / Constituents	Sets of amplitudes and phases describing the changes in tidal elevation based on sinusoidal curves with different periods.

Tidal Regime	The typical tidal pattern at a specific location.
Tolerance	An interval of confidence for a particular dataset.
Topographic	Data describing the changes in surface elevation in relation to a fixed datum.
Truncated Gumbel distribution	A probability distribution whereby the random variable follows the Gumbel distribution truncated at the threshold value from the Peak Over Threshold (POT) analysis.
Weibull distribution	A probability distribution whereby the random variable follows the Weibull distribution.