# CALCULATING EXTREME SEA LEVEL PROBABILITIES AROUND COMPLEX COASTLINES: A BEST PRACTICE APPROACH

Crispian Batstone[1], Mark Lawless[1], Kevin Horburgh[2], David Blackman[2], Jonathan Tawn[3]

[1]*JBA Consulting, Skipton, UK*
[2]*Proudman Oceanographic Laboratory, Liverpool, UK*
[3]*Jonathan Tawn*

## ABSTRACT

The risk of coastal flooding from extreme sea levels affects millions of properties around the world's coastlines. It is therefore prudent to ascertain the probabilities associated with these extreme levels in order to inform coastal flood defence policy. Typically, observational data are sparse and coastlines complex limiting the feasibility of relatively simple routines. Previous work has shown that a Revised Joint Probability Method (RJPM), which exploits knowledge of the interaction between tide and storm surge, offers considerable improvements over annual maximum methods that fit a generalised extreme value distribution (GEV) to observed sea level maxima. This study updates and extends this work to make use of more sophisticated methods and tools available. We adopt three different approaches to estimating the return periods of extreme sea level from quality-controlled tide gauge data. Firstly, we employ functions of the tide to perform a location-scale normalisation of non-tidal residuals and then obtain the distribution parameters using a point-process method; secondly, we construct the joint probability functions of tide and surge directly within a number of discrete tidal bands; finally, we calculate joint probability of the skew surge with the peak tide. The estimates at the gauge sites are more reliable than any previous calculations because of improved methodology and increased length of tide gauge data. A 44-year hindcast data set of sea levels around the coast is produced using high resolution numerical models. This data set of coastal sea variability then provides a means of dynamic interpolation between gauge locations, delivering a consistent spatial method for estimating extreme sea levels around coastlines including complex topographic regions. This method provides the most reliable scientific basis for estimating extreme water levels yet and can be applied to any coastline. The results are directly applicable to coastal flood defence policy.

## INTRODUCTION

Good quality Extreme Sea Level (ESL) estimates are required for coastal flood defence design, flood risk mapping and flood forecasting purposes. ESL estimates calculated for any location are, by their very nature, associated with high levels of uncertainty. This is particularly true in complex coastal regions that can exhibit shallow bathymetry and variable coastlines, where tide and surge processes can change rapidly from one area to the next in non-linear ways. Recorded tide level data has traditionally been the primary source of information used in the calculation of ESLs. Whilst this data has the advantage of being a direct measure of local tides and surges, tide gauge data are sparse, both in time and space. For example there are limited data available for large areas of the Irish coastline. Figure 1 shows the locations of the operational tide gauges that comprise the Irish National Tide Gauge Network. Although there is good spatial coverage in some areas, large areas of coastline in the south and west are as yet not monitored by this network.


**Figure 1: The Irish National Tide Gauge Network (www.marine.ie)**

Typically, the estimation of extreme sea level probabilities at locations between these gauge sites has had to be performed using sparse measurements of tide characteristics in the area (e.g. Mean High Water Springs (MWHS) levels) jointly with an interpolation routine performed along the coastline. An example of such a situation is given in Figure 2. In this example, ESL probabilities can be calculated from the historical time series of still water levels recorded at the tide gauge stations G1 and G2. At locations in between (e.g. towns A and B), the respective probabilities are calculated by a linear interpolation between the values at G1 and G2, dependent on the *coastal distance* (i.e. distance along the dashed line) in between the two gauge sites.

The significant disadvantage of this method is that there is no representation of the dynamic processes that characterize sea level variability along this coastline. In this simplified scenario, the headland at Town A and the bay area at Town B would both cause tidal distortions, leading to lower sea levels at Town A and higher sea levels at Town B than those measured at the nearby tide gauges. Typically there can be some observations along the coastline that can inform the process (e.g. MHWS at a non-standard port P), but such data can sometimes be of dubious quality, and does not provide any information about the characteristics of storm surge variability in the area.

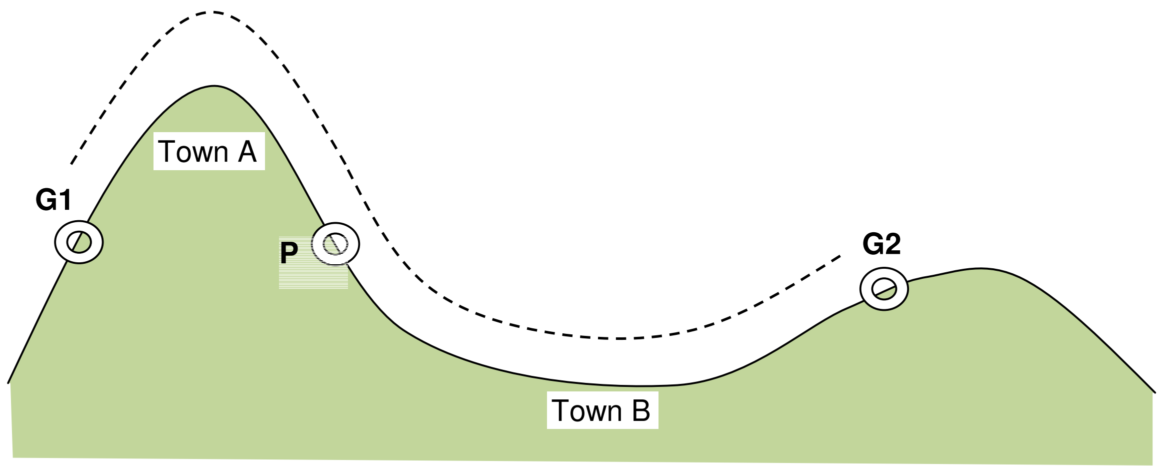


**Figure 2: Example situation of coastal locations where ESL probabilities are to be calculated**

The confidence associated with estimating ESL probabilities in such varying coastal regions has subsequently been low. Improvement to the methods used to derive these estimates is therefore a key area for development, in order to better inform coastal risk management policy.

This paper describes the application of a sophisticated method for estimating ESL probabilities along complex coastlines. First, a description of research into the latest methods for estimating ESL probabilities is given. Then the application of a dynamical ocean model, which simulates tide and surge processes, to produce a high-resolution virtual tide gauge network along the coastline is described. Finally, the adjustment of the model output to observed gauge data values is explained. The method has been used to produce a consistent database of ESL probabilities around the coast of Ireland.

## ESTIMATION OF EXTREME SEA LEVEL PROBABILITIES AT GAUGE SITES

### Annual Maximum Generalised Extreme Value (AMAX GEV) method

Historically, ESL probabilities have been calculated by fitting a GEV (or Gumbel) distribution to records of the highest sea level for each year of data available. Whereas this method is useful at locations where only this AMAX data is available, it leads to probabilities that are highly sensitive to the number and value of observations used, and thus exhibit large uncertainties. At locations where higher temporal resolution sea level data is available this method is extremely wasteful. For instance, two very high sea levels may occur within one year, yet only one of these levels would be included in the ESL estimation, possibly leading to an underestimation of the frequency with which such levels occur. Moreover, the technique is not informed by data gathered on the behaviour of storm surges in the area. A large storm surge event may have accompanied a low tide level during the observational period, which would not produce a significantly high water level. The possibility of such an event occurring at high tide and consequently leading to a very high sea level is not accounted for by the AMAX GEV technique.

### POL Advanced Joint Probability method / Revised Joint Probability method

Extreme sea level occurrences depend upon both tidal processes and storm surges – the effect of transient weather systems on the sea surface. Therefore it is informative to investigate the probabilities of the co-occurrence of high levels for both of these components. An accepted method for combining the deterministic tidal distributions with stochastic storm surge distributions is the joint probability method (JPM)[i]. At a given location, the JPM effectively calculates the joint probability table for all combinations of tide and non-tidal residual (often termed 'surge residual') within an observational record (i.e. from a tide gauge). The probability of any extreme sea level being reached can then be calculated from this combined level distribution.

A key issue in a JPM is the treatment of the non-tidal residual (i.e. the time series obtained by subtracting tidal predictions from the observed sea levels). Many properties of the residual time series are an artefact of small changes to the timing of predicted high water, combined with the fact that wind stress is most effective at generating surge around low water. It is well known that at many tide gauge locations peak non-tidal residuals are consistently obtained 3-5 hours before tidal high water (Horsburgh and Wilson, 2007)[ii]. It is important to consider these tide-surge interaction characteristics when calculating the joint probability of surge and tide. For instance, if large non-tidal residuals observed at mid-tide levels were an artefact of a timing error, it would be inaccurate to associate these values with physical large surge events and subsequently examine the probability of such events occurring at high tide.

The POL (Proudman Oceanographic Laboratory) Advanced JPM (an enhancement of the widely-used POL112 method) and the Revised JPM[iii] both take into account tide-surge interaction in the joint probability calculation. The POL method fits a tide-surge interaction function in order to create a distribution of residual that smoothes out the effects of tide-surge interaction, allowing as much of the statistical information to remain whilst precluding false values of residual from entering the high water joint distribution function. The RJPM deals with the issue by calculating the joint probabilities within discrete bands of the tide level range. This ensures that large residuals that typically occur at mid-tide are not included in the statistical distributions for high water.

A benefit of these approaches is that they use all samples from a tide gauge record to inform the calculation of the statistical distribution of extreme sea levels. These data-rich methods therefore provide much narrower confidence limits on the estimated ESL probabilities than data-sparse methods (e.g. AMAX GEV). However the need to account for tide-surge interaction in the computation requires empirical methods that are tuned differently for each gauge site analyzed.

**Skew Surge Joint Probability Method**

The Skew Surge Joint Probability Method (SSJPM) is a third JPM, which utilizes the 'Skew Surge' parameter to calculate the distribution of extreme sea levels. The Skew Surge (Figure 3) is the difference between the predicted high tide level and the highest tide level observed over the period of the semi-diurnal tide. Its value is therefore not affected by time differences between the observed and predicted tidal values, unlike in the calculation of the non-tidal residual. The JPM calculates the joint probability between Skew Surge and predicted tide maxima in order to derive the distribution of high waters.

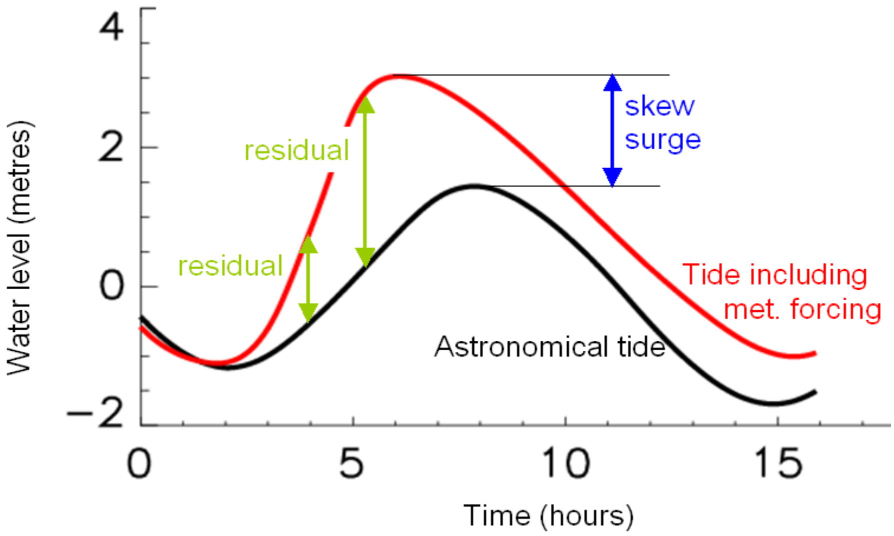


**Figure 3: Illustration of the Skew Surge parameter**

The rare nature of extreme sea levels means that there are few events recorded to fully resolve the extreme tail of the Skew Surge distribution. Therefore a Generalized Pareto Distribution is fit to this tail to provide this increased resolution.

The method is simpler than the two other JPMs as it does not require analysis and parameterization of the effects of tide-surge interaction on the high water distribution. This is because the Skew Surge parameter eliminates discrepancies due to timing differences in the observed tide from that predicted. It is also because the method examines the characteristics of tides and surges at high tides only: tide-surge interactions that may lead to large surges that occur only at low tides and subsequently do not lead to high water levels are ignored. The SSJPM is therefore the preferred method for calculating ESL probabilities.

## ESTIMATION OF EXTREME SEA LEVEL PROBABILITIES ALONG COASTLINES

The calculation of ESL probabilities using the SSJPM requires a high temporal resolution time series of sea level. At coastal locations between gauge sites a dense network of virtual gauge sites can be constructed using a hydrodynamic tide-surge model.

### Tide-Surge Model

The astronomical tide and meteorological surge processes at the coastline are simulated using a two-dimensional, depth-averaged version of the finite-difference Princeton Ocean Model. The tide processes are modelled by supplying the relevant harmonic constituents at the ocean boundary. The response of the ocean to atmospheric influence is simulated in the model by forcing the model at the ocean-atmosphere boundary with historical surface wind and air pressure. This hindcast meteorological data is supplied by the European Centre for Medium-range Weather Forecasts 40-year reanalyses (ERA-40) and USA National Centers for Environmental Prediction reanalyses data. An example of an implementation of such a tide-surge model is JBA's North West European Shelf model. This model provides a virtual tide gauge network around the Irish and UK coastlines at approximately a 4 km resolution.

Two model runs are performed: astronomical tide forcing only and tide forcing with meteorological forcing included. These two runs provide the simulated tide level and total sea level over the model domain respectively. The Skew Surge values for use in the joint probability analysis are subsequently calculated from these two data sets.

**Model Calibration and Validation**

Observational data provided by tide gauges at the coast is necessary to calibrate and validate the performance of the tide-surge model. An example of how the model performs against 36 years of hourly resolution gauge data at Aberdeen is shown in Figure 4. The model simulates the range of tide and surge events to a very good degree of accuracy.

**High Resolution Models**

In areas of complex coastlines the North West European Shelf model may not exhibit fine enough spatial resolution to accurately simulate oceanic processes. In these areas a separate tide-surge model can be developed that takes oceanic conditions at its ocean boundary from the coarser North West European Shelf model. Such models have been developed for the North East Irish Sea and Loch Linnhe in western Scotland amongst others.

**Return Period Adjustment**

Although the model is calibrated using time series of sea level recorded at tide gauge stations, it will still retain some inaccuracies due to the modelling assumptions used (e.g. coarse resolution meteorological and bathymetric data, 2D depth-averaged physics, etc.). Therefore an adjustment is made in order to tune the model to reality. ESL probabilities are calculated at all required coastal model points as well as relevant tide gauge stations. The level probabilities derived from the observed gauge data are then used to correct those derived from the nearest model point. Figure 5 shows an example of the error between the gauge-derived and model-derived ESL probabilities. This error value, taken at two gauge sites, is then used to correct all model-derived ESL probabilities for all intermediary grid points, by interpolating along the coastal distance between the gauge sites.

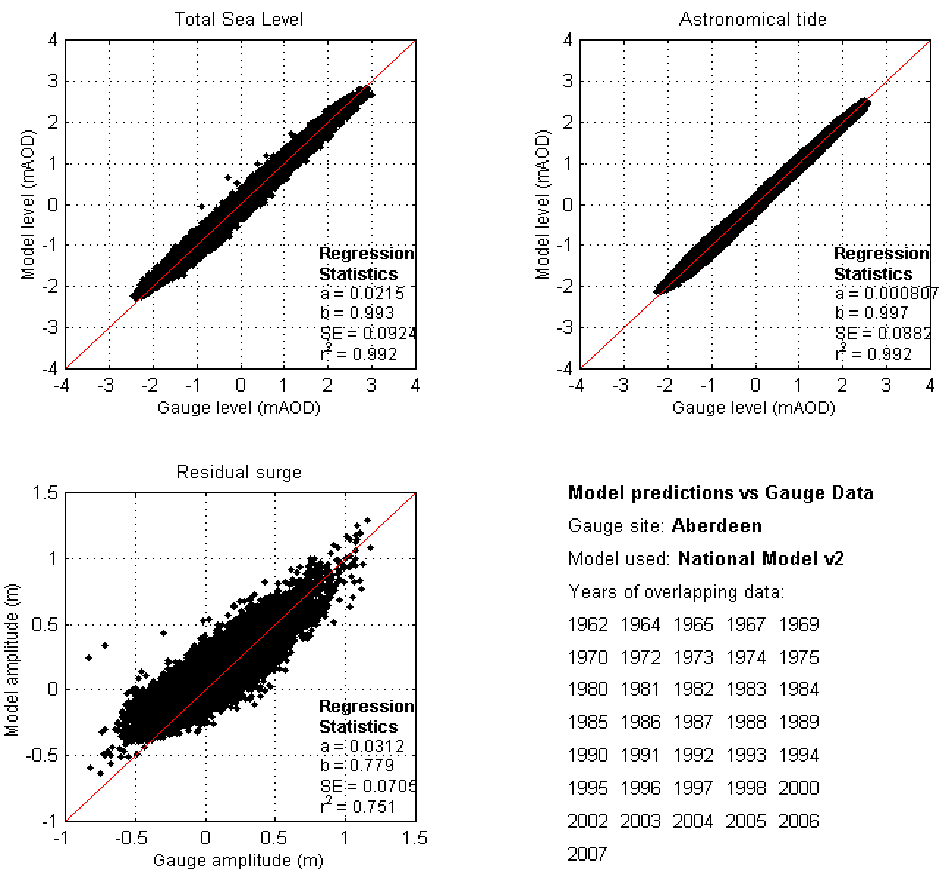


**Figure 4: Model vs Gauge comparison at Aberdeen**

**Application to Ireland**

The method outlined has been used by JBA to produce a high resolution database of ESL probabilities for the coastline of Ireland (Figure 6). The model data was adjusted using high resolution tide gauge data provided by the Marine Institute at several locations around the coast (Figure 1). Validation was performed using AMAX data at Dublin and Galway. The database can be used to inform coastal flooding risk and coastal management policy.

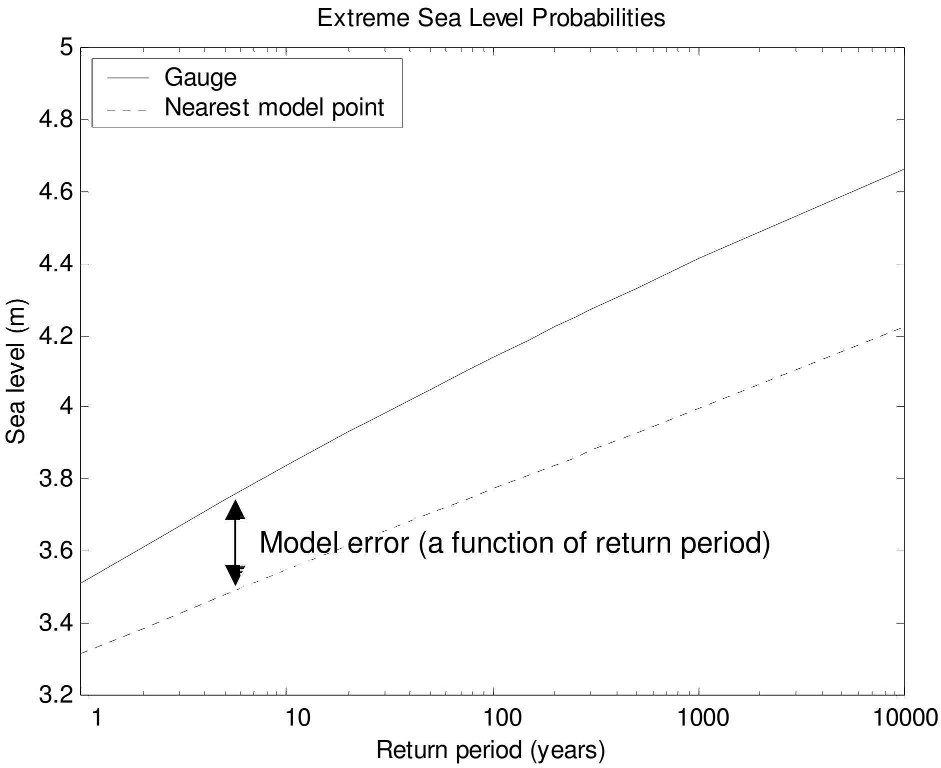


**Figure 5: Gauge vs Model ESL probabilities**

## SUMMARY

We have developed a consistent spatial method to deliver reliable estimates of ESL around complex and varying coastlines. This paper provides an outline of this method, which exhibits greater confidence than methods which have previously been available. The method calculates the probability of high water at tide gauge stations using a joint probability calculation between the Skew Surge and predicted high tide values. A Generalized Pareto Distribution is fit to the extreme tail of the Skew Surge parameter to provide increased resolution of the probabilities of extreme levels. A numerical, hydrodynamic model is run using hindcast meteorological data to produce a multi-year, high spatial resolution, virtual tide gauge network along the coastline. The ESL estimations at these model grid points are then adjusted using the error in the calculation of the model ESLs at nearby gauge sites. The calculated ESL probabilities can then be used to inform flood defence design, emergency planning and development planning. The method has been used to produce a consistent database of ESL probabilities around the coast of Ireland.

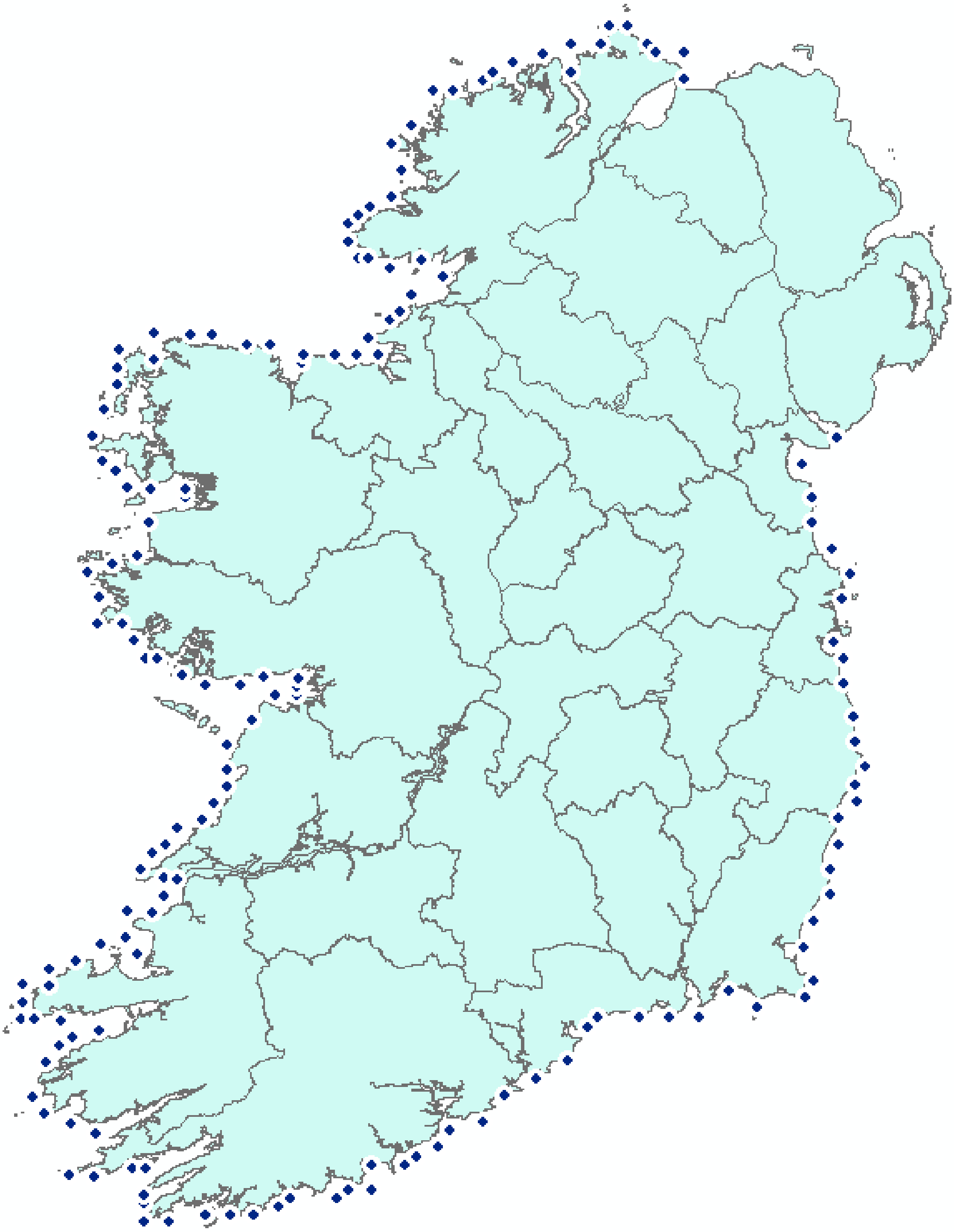

**Figure 6: Extreme sea level probability calculation sites for the JBA Irish ESL database**

**ACKNOWLEDGEMENTS**
Tide gauge data for the production of the Irish Coastal ESL database was provided by the Marine Institute. Meteorological data was supplied by ECMWF and NCEP. Bathymetry data was provided by Seazone Solutions Ltd, the BODC and the BGS. Funding for the enhancement of the method was provided by the Environment Agency funded project, 'Coastal and Estuary Extremes (SC060064)'.

**REFERENCES**

[i] Pugh, D. T., and J. M. Vassie (1980), Applications of the joint probability method for extreme sea level computations, Proceedings of the Institution of Civil Engineers, 69, 959-975

[ii] Horsburgh, K.J. and Wilson, C. (2007) Tide-surge interaction and its role in the distribution of surge residuals in the North Sea. Journal of Geophysical Research Oceans, 112, C08003, doi:10.1029/2006JC004033

[iii] Tawn, J. A. and Vassie, J. M (1989) Extreme sea levels: the joint probability method revisited and revised. Proceedings of the Institution of Civil Engineers, 87, 429-442