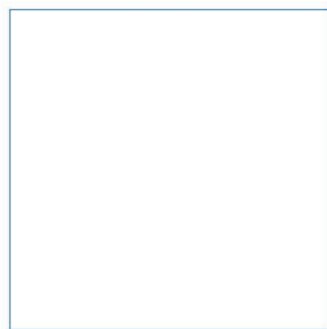
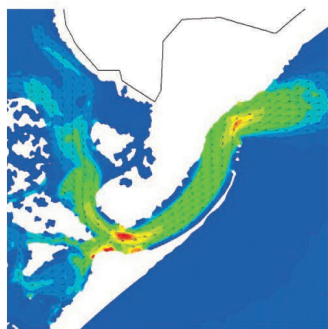
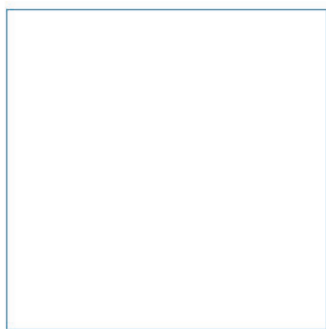
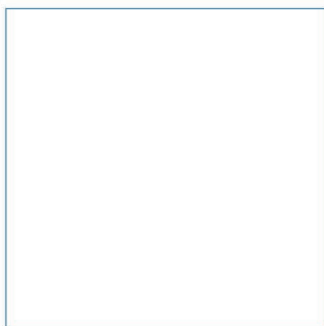


# Barmouth North Promenade

Wave modelling, extremes analysis and overtopping

May 2019



Innovative Thinking - Sustainable Solutions

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Wave modelling, extremes analysis and overtopping

May 2019



# Document Information

| Document History and Authorisation |                                                   |                              |
|------------------------------------|---------------------------------------------------|------------------------------|
| <b>Title</b>                       | Barmouth North Promenade                          |                              |
|                                    | Wave modelling, extremes analysis and overtopping |                              |
| <b>Commissioned by</b>             | Arup                                              |                              |
| <b>Issue date</b>                  | May 2019                                          |                              |
| <b>Document ref</b>                | R.3105                                            |                              |
| <b>Project no</b>                  | R/4666/02                                         |                              |
| Date                               | Version                                           | Revision Details             |
| 08/02/2019                         | 1.0                                               | Preliminary working document |
| 25/03/2019                         | 2.0                                               | Issued for client review     |
| 22/05/2019                         | 3.0                                               | Issued for client use        |
|                                    |                                                   |                              |
|                                    |                                                   |                              |

| Prepared (PM)                                                                     | Approved (QM)                                                                     | Authorised (PD)                                                                     |
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## Suggested Citation

ABPmer, (2019). Barmouth North Promenade, Wave modelling, extremes analysis and overtopping, ABPmer Report No. R.3105. A report produced by ABPmer for Arup, May 2019.

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## Units

All depth and heights are referenced to ODN unless otherwise stated.

# 1 Introduction

ABPmer has been commissioned by Ove Arup and Partners Limited (Arup) to review the coastal processes at Barmouth, to determine the nearshore wave and water level conditions and to undertake overtopping analysis. The overtopping analysis has been undertaken for the existing defence and a series of defence options for present day (epoch 2019) and with an allowance for climate change over 50 and 100 years (epoch 2069 and 2119 respectively). The work contributes to the development of an Outline Business Case (OBC) for flood and erosion protection at Barmouth. The OBC was commissioned by Ymgynghoriaeth Gwynedd Consultancy (YGC); part of Cyngor Gwynedd Council (CGC). Understanding the wave climate and overtopping volumes are essential for CGC in developing options available for the North Promenade.

This work is reported in two separate deliverables:

- **Process Understanding** (separate document, ABPmer 2019) - A summary of the coastal processes affecting the defences and the conceptual understanding of the dynamics at North Promenade, and the wider area.
- **Wave Modelling, Extremes Analysis and Wave Overtopping** (this document) - A report which sets out the modelling results for the wave, water level and wave overtopping criteria of the Barmouth North Promenade frontage.

A regional wave model of Cardigan Bay has been refined around Barmouth to generate a long term hindcast database of wave conditions along the Barmouth Frontage allowing a robust statistical assessment of the wave climate to be carried out. The study area is shown in Figure 1 and Figure 2. The model area and extent is shown in Figure 3.

The modelling study has been undertaken using the Danish Hydraulic Institute (DHI) software package MIKE21 FM (Flexible Mesh). The modelling system was developed by MIKE DHI for complex applications within oceanographic, coastal and estuarine environments. For the present study, the MIKE21 SW (Spectral Wave) module has been used. MIKE21 SW is a new generation spectral model based on an unstructured mesh which simulates the growth, decay and propagation of the swell and wind generated waves in offshore and coastal areas.

This report provides a description of the wave model setup, extreme value analysis, transformation of waves to the coastal defence and overtopping analysis at the Barmouth Frontage.

The analysis and associated documents provide information to support the assessment of the existing situation, the flood inundation modelling being undertaken by Arup, and the development of protection options.

## 1.1 Site description

This section provides a short description of the bay, further description and details of the coastal processes, hydrodynamics and wave climate are provided in ABPmer (2019).

Barmouth North Promenade is located in Cardigan Bay, between Llanaber in the north, and River Mawddach to the south (Figure 1). The North Promenade frontage is approximately 1,300 m long and faces south south-west (SSW). It extends from a residential housing estate at Heol y Llan to the northern extent of the promenade wall.

The defence protects a mixture of commercial and residential developments and the beach fronting the defences is used extensively by tourists and helps contribute significantly to the local economy.

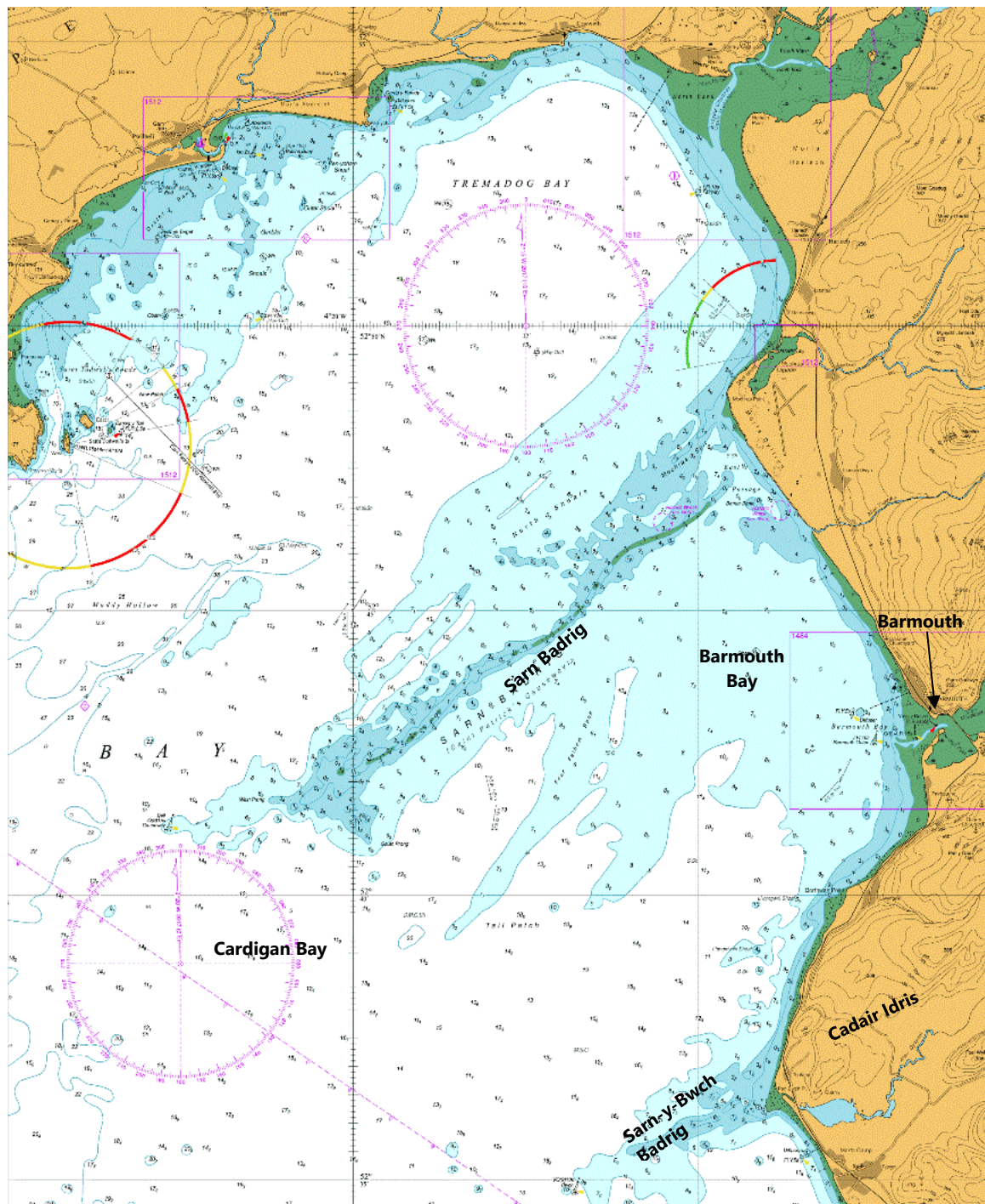
The beach north of North Promenade is comprised of a shingle/cobble bank that fronts the railway line. Along North Promenade and to the south of North Promenade, the sediments are mainly comprised of sand with isolated pockets of shingle/cobbles along the upper foreshore.



**Figure 1.** Location of Barmouth North Promenade with historical names and sediment regions (sand and shingle) and SMP2 policy units: **Llanaber (11.16)**, **Barmouth North (11.15)** and **Barmouth South (11.14)**

To the south, the Mawddach Estuary, is designated as a Site of Special Scientific Interest (SSSI) and as a Special Area of Conservation (SAC), whilst the whole of Cardigan Bay forms part of the Llŷn Peninsula and Sarnau SAC. Most of the beach is above mean high water and the dunes do not have nature conservation designation, but the dunes are priority Biodiversity Action Plan (BAP) features which are now relatively scarce in Wales and across Europe. These dunes consist of dynamic foredunes and embryo dunes. At the outer edge of Cardigan Bay, the sea bed lies in depths of approximately 30 m. Depths then decrease eastwards in towards Barmouth Bay.

Barmouth Bay itself, is located between two headlands which extend offshore as shallow causeways. To the north the headland forms a continuous ridge running in a south westerly direction from Morchrass Point along Sarn Badrig (St Patrick's Causeway). To the south the shallow causeway Sarn-y-Bwch, extends from Pen Bwch Point. The Mawddach River and Estuary are situated between these two constraining geological features (Figure 2). The shallow ridges to the north and south (Figure 2) influence the wave energy that reaches Barmouth, restricting wave energy that can reach the site from more north westerly and southerly direction sectors. At the mouth of the Mawddach estuary a series of large sandy shoals exist. These sandy shoals form part of the ebb delta system that fronts the estuary mouth and are highly dynamic.



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Figure 2. Bathymetric chart from 1971

## 2 Wave Model Configuration

### 2.1 Grid design

ABPmer's regional scale Cardigan Bay model has been refined around the Barmouth Frontage.

The Cardigan Bay model has boundaries at the western tip of the Llyn Peninsula in the north and Cardigan in the south. The model incorporates the most up to date bathymetry from the EMODnet Portal, supplemented with digitised data from UKHO Chart 1971 around the area of interest.

The Cardigan Bay model, refined around Barmouth is shown in Figure 3.

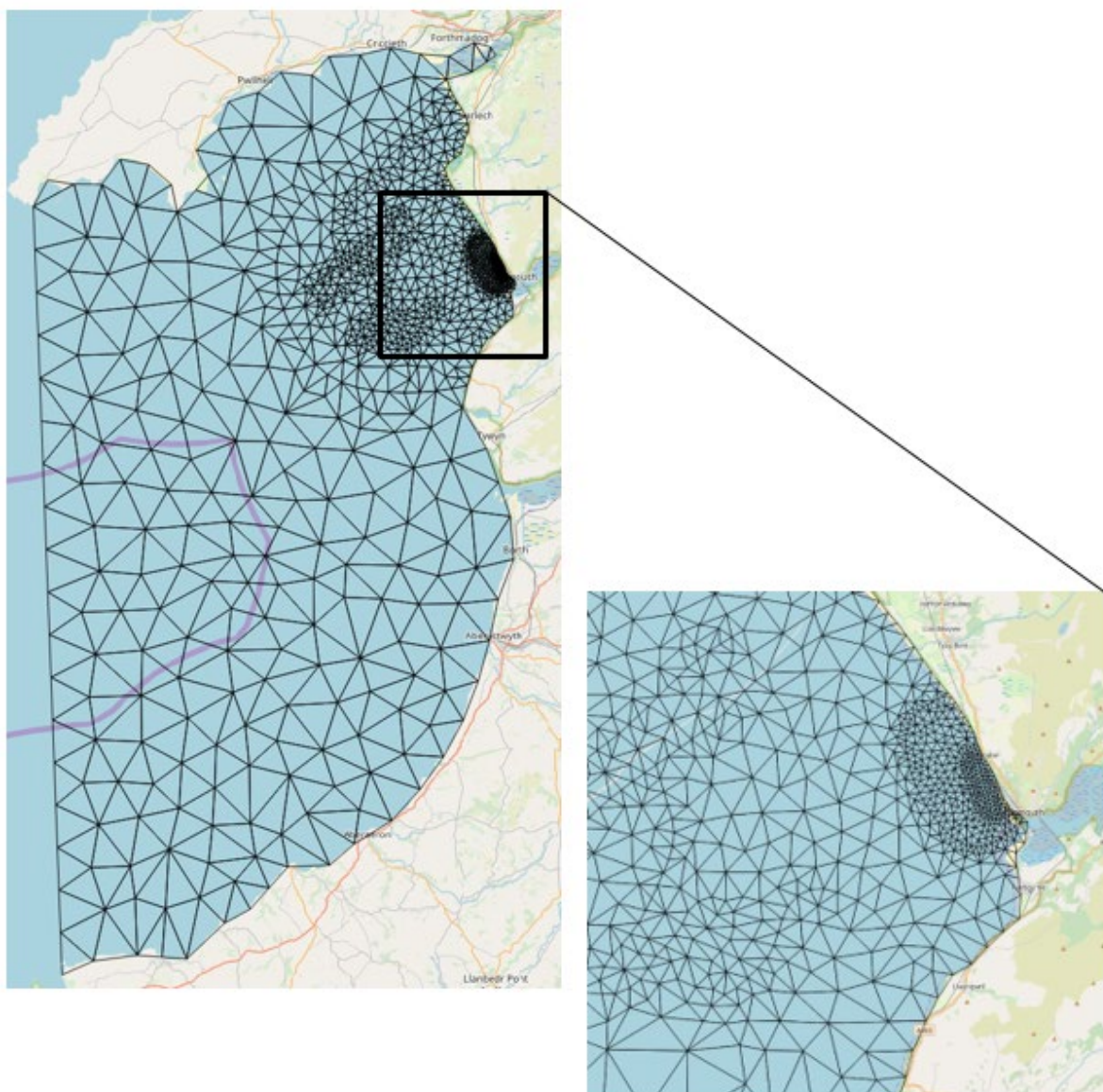


Figure 3. Map of refined Cardigan Bay model mesh

The model has been created using a flexible mesh approach which allows the size of the 2052 grid cells to be varied across the model domain, thereby maximising computational efficiency. The mesh resolution ranges from ~4 km at the outer sections, which is sufficient to accurately capture the transformation of waves around the boundaries, to ~150 m at the Barmouth Frontage. The varying resolution of the model has been carefully linked to the local bathymetry to ensure that regions of varying bathymetry such as Sarn Badrig are adequately resolved in the model, enabling wave processes to be reliably reproduced throughout the model domain. The model extent and mesh resolution is shown Figure 3.

## 2.2 Bathymetry

The bathymetry used in the model is derived from the sources below:

- Data digitised from UKHO Chart 1971 for areas close to Barmouth.
- For the general Cardigan Bay area, data from the European Marine Observation and Data Network (EMODnet) (<http://www.emodnet.eu/>) was utilised.

All data sets were converted to Ordnance Datum Newlyn (ODN) prior to being included in the wave model. During development of the model bathymetry the data was interpolated on to the model mesh in the following order of priority:

- UKHO Chart 1971
- EMODnet (<http://www.emodnet.eu/>).

The model bathymetry is shown in Figure 4.

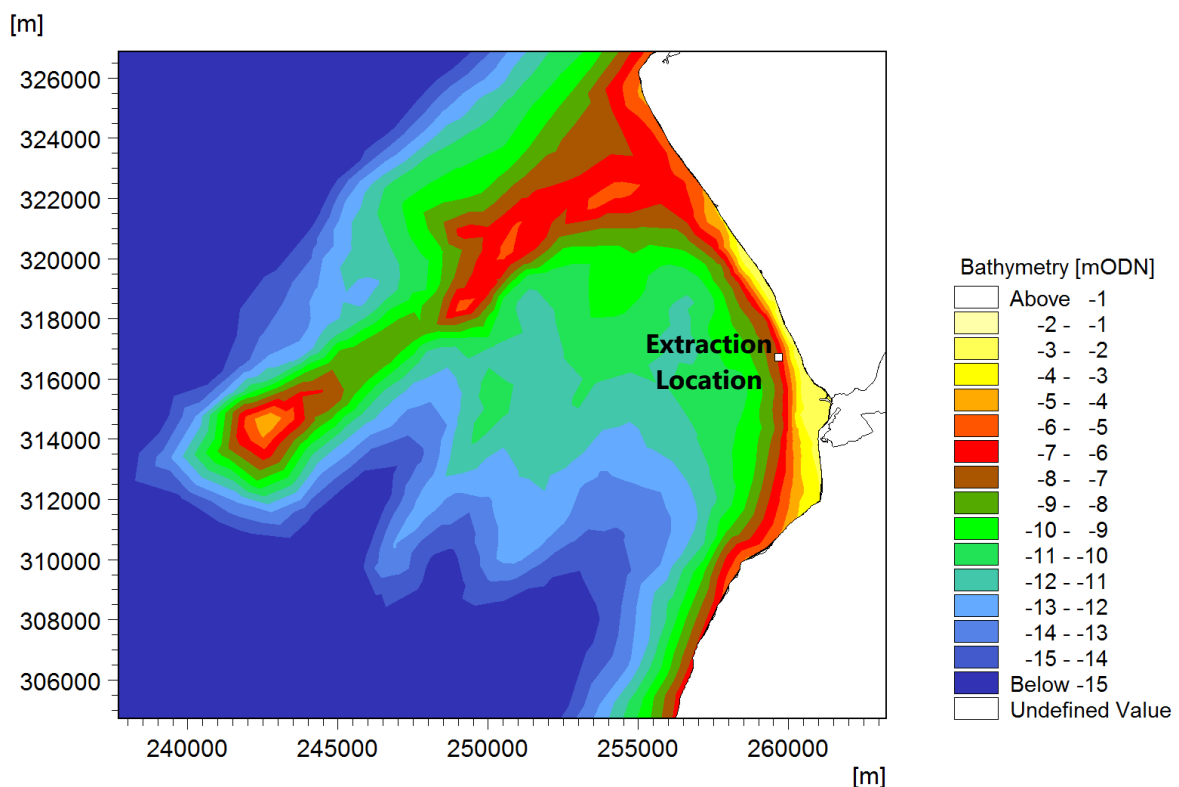


Figure 4. Model bathymetry with -7 mODN extraction location

## 2.3 Wave boundaries

Wave conditions for this model boundary were extracted from the ABPmer SEASTATES hindcast service (detailed below). These are provided in the form of wave parameters, separated into wind and swell sea components.

SEASTATES ([www.seastates.net/](http://www.seastates.net/)) is a service provided by ABPmer to supply metocean information to support site characterisation, project design or operational planning around the UK (ABPmer, 2013). SEASTATES includes a long-term (39 year) wave hindcast database driven by wind fields derived from the NCEP ‘Reanalysis II’ hindcast datasets of spatially and temporally varying winds. This allows a long term hourly dataset of wave parameters, including significant wave height, maximum wave height, wave period and wave direction to be created for a specific location. In addition to the standard wave parameters, spectral wave parameters are available along fixed boundary locations around the UK coastline. Validation plots and statistics of the SEASTATES model at the M2 and M5 wave buoys are found in Figure 5 and Figure 6 respectively. Full details of the setup, calibration and validation of the SEASTATES Wave Hindcast model can be found in ABPmer (2013).

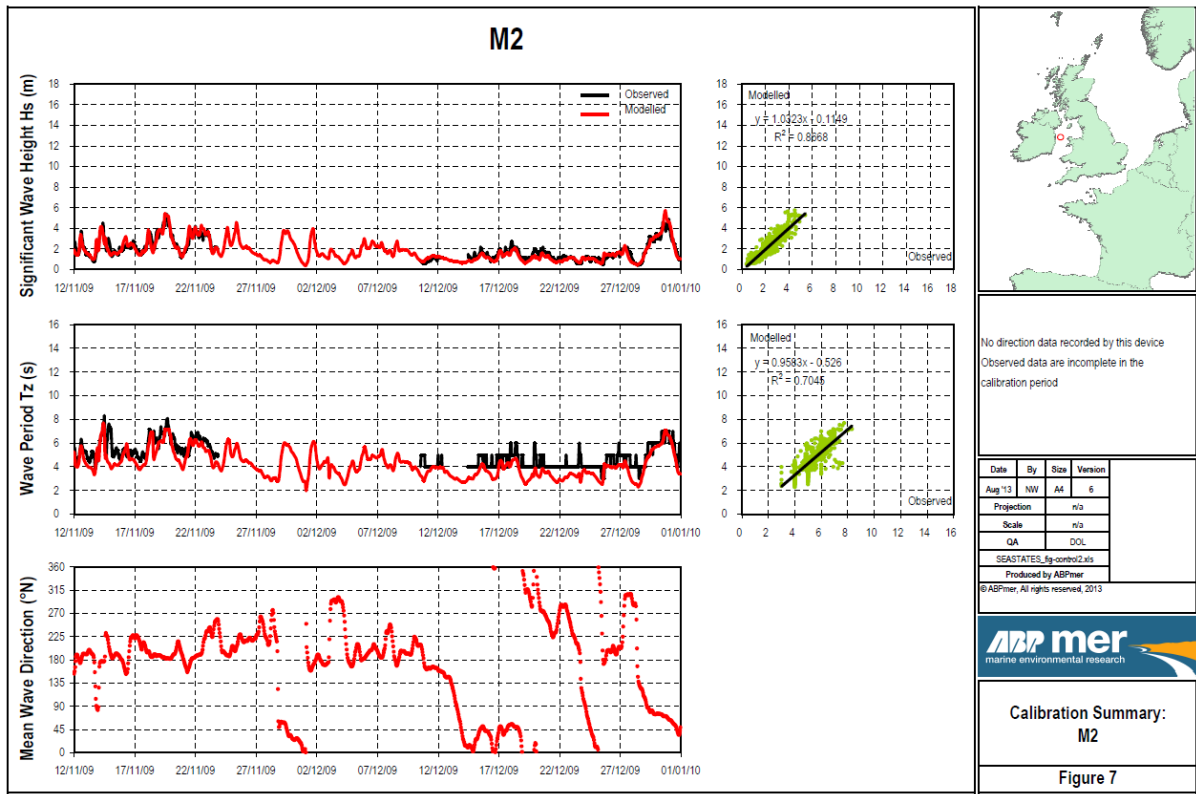
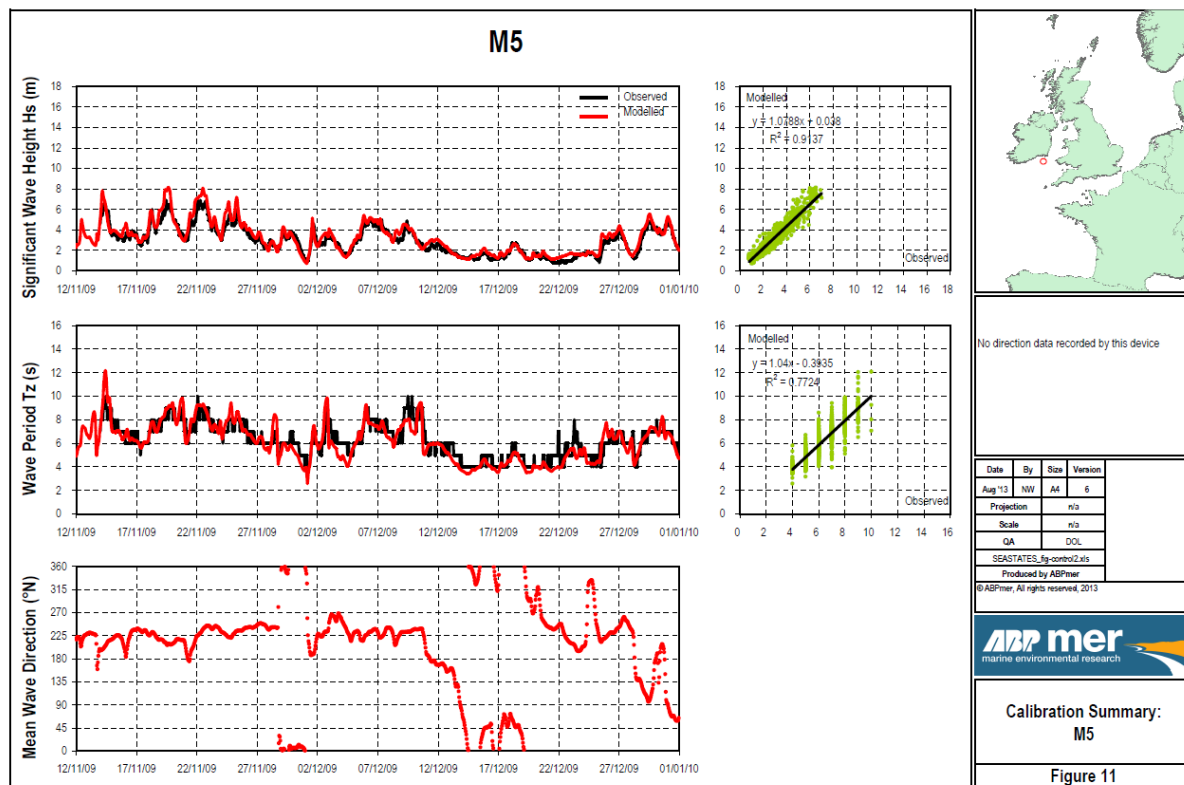


Figure 5. Validation of SEASTATES wave model at M2 wave buoy



Source: ABPmer, 2013

**Figure 6. Validation of SEASTATES wave model at M5 wave buoy**

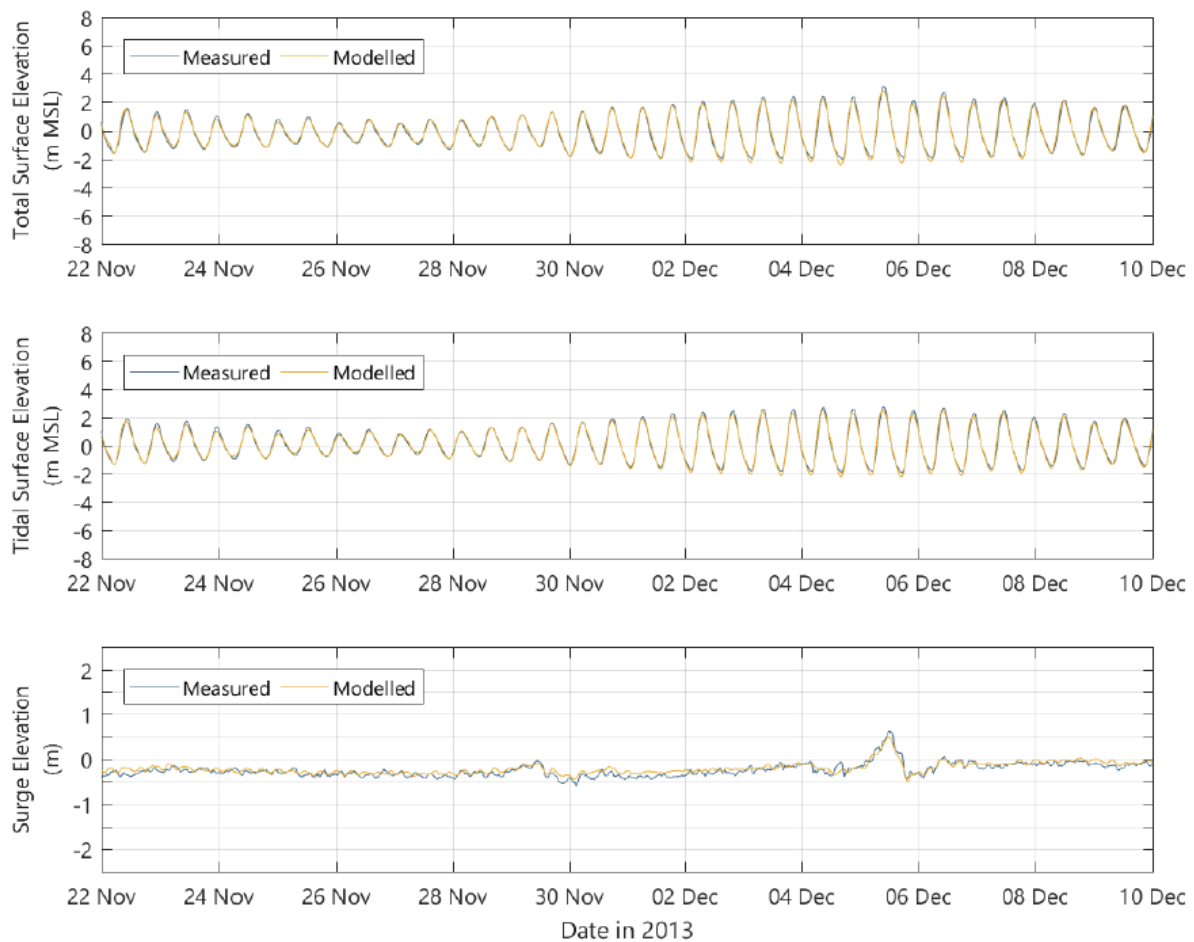
## 2.4 Water levels

Due to the shallow water environment, near to Barmouth, tidal levels have the potential to significantly alter the transformation of the waves as they travel inshore. It is therefore important to include time varying water levels which are representative of the Barmouth Frontage over the model domain for the duration of the hindcast simulation.

For the modelling, a 39 year hindcast of predicted total water level (tide + surge) was extracted from the SEASTATES tide and surge model for a single location directly off the Barmouth Frontage. These water levels were then applied over the full model domain during the model simulations.

The ABPmer SEASTATES Tide and Surge model is a hindcast hydrodynamic model, providing water level and current data across the North East European continental shelf for the period 1979 to present. This provides a continuous and consistent water level database covering the same period as the SEASTATES hindcast wave model.

The SEASTATES Tide and Surge model has been calibrated and validated against numerous level and current data sources around the UK and European coastlines. This included a comparison with the measured gauge data, which shows that the model reliably reproduces both the tide and surge that is observed at Barmouth (Figure 7). Full details of the setup, calibration and validation of the SEASTATES Tide and Surge model can be found in ABPmer (2017).



Source: ABPmer, 2017

Figure 7. Validation of SEASTATES tide and surge model at Barmouth tide gauge

## 2.5 Wind forcing

Long term hindcast wind speeds and directions are available from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (<http://rda.ucar.edu/datasets/ds093.1/>) and Climate Forecast System v2 (CFSv2) (<http://rda.ucar.edu/datasets/ds094.1/>) hindcast databases. The data archive is managed by the National Center for Atmospheric Research (NCAR). CFSv2 hindcast data are available from 1979 to December 2010 at 0.2° spatial resolution as hourly timeseries. CFSR data are available from January 2011 to present

The pre and post 2011 hindcast datasets were compared with available overlapping measured datasets to ensure there was consistency over the transition period. The two data sets were found to be consistent and therefore provide a single continuous long-term hindcast dataset of wind speed and directions. For simplicity, this dataset is referred to as CFSR from this point onwards.

This CFSR long term global hindcast of wind data was utilised to provide wind forcing for the study.

## 2.6 Sensitivity testing

At the start of the calibration process a series of initial model sensitivity tests were undertaken to examine the influence of several model parameters including model resolution, bed resistance, directional discretisation and frequency discretisation.

A one-month period with a large sea-state (December 2013) was chosen to test the sensitivity of the model. The sensitivity tests showed that bed roughness has a significant effect on the wave heights produced at Barmouth whereas mesh resolution, directional discretization and spectral discretization produce reasonably consistent results with increasing resolution.

Guidance from the DHI Spectral wave model suggests the default Nikuradse roughness of 0.04 m is known to be too high for nearshore applications and will underestimate wave heights. Bed roughness is also difficult to assess, and therefore should be used as a calibration factor. As measured wave data is not available at Barmouth, knowledge from past projects has been used to test a sensible range of Nikuradse roughness values. Following these tests, a Nikuradse roughness of 0.001 m has been chosen for the model.

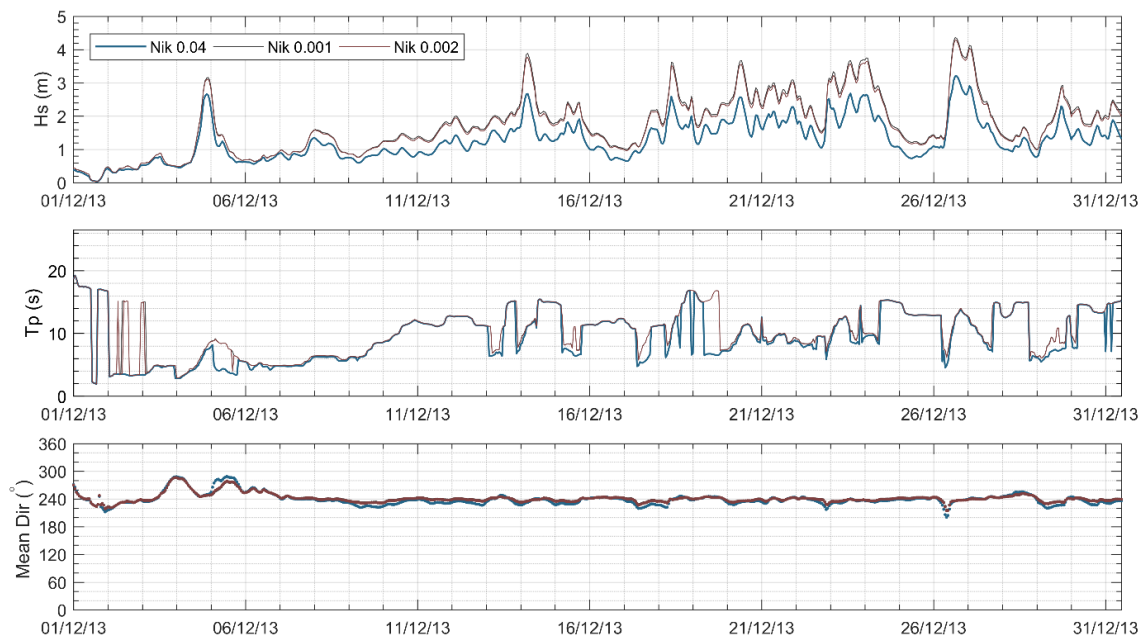


Figure 8. Bed roughness sensitivity test

## 2.7 Climate change

Three epochs (2019, 2069 and 2119) were considered in the hindcast and Extreme Value Analysis (EVA). To achieve representative climate change allowance for each epoch, climatic variables were considered in relation to the spectral wave modelling to derive total water levels at the site because of changes to offshore wind and wave conditions.

For the 2069 and 2119 epochs, the model has been run to derive the full 39 year hindcast with the following adjustments:

- Water levels across the model domain increased to accommodate Mean Relative Sea Level Rise (MRSL) to 2069 and 2119 epochs respectively; and
- No wind/wave increases.

The current industry guidelines in relation to climate change are those provided in Welsh Government (2017) 'Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities'. This guidance is to be used by risk management authorities when making investment decisions.

### 2.7.1 Mean relative sea level change

In accordance with Welsh Government (2017), the UKCP09 Medium Emission Scenario was used to derive the water levels to account for MRSLR.

This guidance does not provide details as to how to extrapolate past 2116. Therefore, the way this has been considered is provided in the sections below.

A single regional allowance for the annual change for the Welsh coastline is given in Welsh Government (2017) and is shown in Table 1.

**Table 1. Mean sea level allowance (Adapted from Welsh Government (2017))**

|                       | Sea Level rise up to 2025 (mm/yr) | Sea Level Rise 2026 to 2055 (mm/yr) | Sea Level Rise 2056 to 2085 (mm/yr) | Sea Level Rise 2086 to 2116 (mm/yr) |
|-----------------------|-----------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Annual Change (mm/yr) | 3.5                               | 8.0                                 | 11.5                                | 14.5                                |

This annual change in sea level has been used to calculate increases in water level to be applied to the wave hindcast model for the three epochs (Table 2). These increases in water level have been added to CFBD 2008 point 835 to predict extreme water levels at the Barmouth frontage.

**Table 2. Increases in water level applied to wave hindcast model**

|                                           | Epoch 2019 | Epoch 2069 | Epoch 2119 |
|-------------------------------------------|------------|------------|------------|
| WL increase from base date of 2008 (mODN) | 0.039      | 0.461      | 1.138      |

### 2.7.2 Wind/wave climate change

Welsh Government (2017) guidance states:

*"Change to wave climate is presented within UKCP09. There are large uncertainties especially with the projected extreme values.*

*Projections of changes to wave climate in UKCP09 are given for return periods up to 50 years. Projections of longer return period wave heights will reflect the same pattern of change but with larger error bars. Changes in wave period and direction are small and more difficult to interpret.*

*Due to the significant uncertainty both to the future position of the storm track over the UK and the projections of wave climate within UKCP09, it is recommended that RMAs employ a sensitivity analysis to understand the impact on flood risk and coastal change, and the form of any feasible options. Recommended national precautionary sensitivity ranges for offshore wind speed and wave height are presented in Table 5."*

| Parameter           | Sea Level Rise up to 2025 (mm/yr) | Sea Level Rise 2026 to 2055 (mm/yr) | Sea Level Rise 2056 to 2085 (mm/yr) | Sea Level Rise 2086 to 2116 (mm/yr) |
|---------------------|-----------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Offshore wind speed | +5%                               |                                     | +10%                                |                                     |
| Extreme wave height | +5%                               |                                     | +10%                                |                                     |

**Table 5 Recommended national precautionary sensitivity ranges for offshore wind speed and wave height (Welsh Government, 2017)**

The same guidance is also provided in Environment Agency (2011). However, no guidance is provided as to how the sensitivity should be considered. There is significant uncertainty associated with the % increase in wind and wave parameters and these can result in significantly larger increases in the wave climate for the future epochs. As such, it is considered appropriate for wind and wave increases to be considered as a sensitivity test rather than included in the future 39 year hindcasts. The results of the sensitivity test can be used to give a judgement of the likely effect of a change in wind conditions on the no wind modelled results.

### 2.7.3 Wind/wave increase sensitivity test

A sensitivity test has been undertaken for a single year (2014) of the hindcast timeseries. The 2119 epoch has been chosen for the sensitivity test and hence wind speeds and the wave height at the model boundary were increased by 10 % as recommended in Welsh Government (2017).

An average wave height increase of 8 % is seen at the Barmouth frontage when winds and the model wave boundary is increased by 10 % (Figure 9).

It is important to note that this sensitivity test looks at a single condition which is deemed proportionate at OBC level.

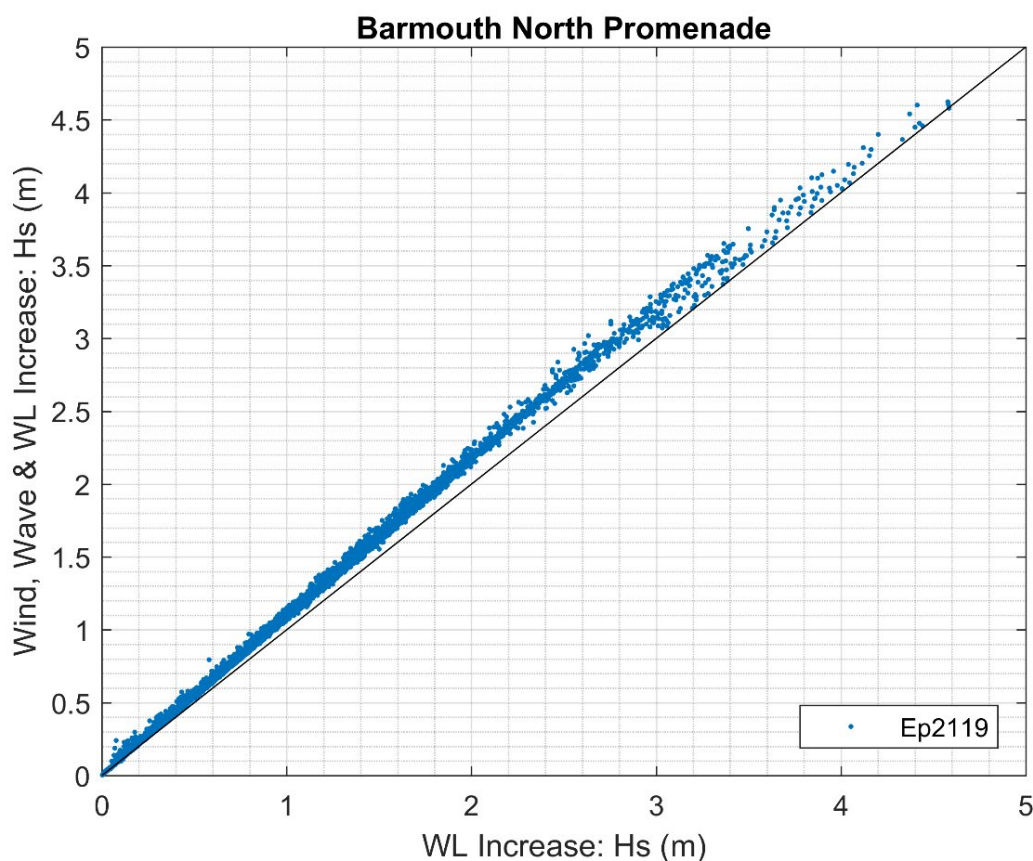


Figure 9. Scatter plot showing difference in significant wave height offshore Barmouth when increasing wind and waves at boundary by 10%

## 3 Model Results

### 3.1 Hindcast predictions

A time-series of wave parameters at a single extraction location on the -7 mODN contour, has been extracted from the Cardigan Bay wave model and is shown in Figure 10.

For each epoch (2019, 2069 and 2119), the following results are presented:

- Scatter plot of significant wave height ( $H_s$ ) vs wave energy period ( $T_{m-1,0}$ ) (Figure 11);
- Wave rose (Figure 12); and
- Map of significant wave height showing spatial variation during February 2014 storm event.

The Barmouth Frontage is affected by a mixture of swell waves originating in the Atlantic and wind waves from the Irish sea and Cardigan Bay, with the maximum  $H_s$  in the present day 39-year model record being 4.2 m at the -7 mODN contour. This event has a corresponding  $T_{m-1,0}$  of 12 s.

Nearshore the dominant wave direction is from the southwest with a mean wave direction of  $244^\circ$ , due to the offshore prevailing wave conditions. Sarn Badrig to the north also inhibits the wave energy reaching the site from more north westerly direction sectors.

The wave climate at the Barmouth North frontage is predicted to increase in 2069 and 2119 due to sea level rise. Wave direction is largely unaffected by increases in water level.

Other than the local shoals near the mouth of the Mawddach Estuary, the bathymetry directly off the North Promenade frontage is relatively smooth and featureless. Therefore, the dominant wave energy approach the frontage from a relatively consistent angle that is close to shore normal (Figure 13 to Figure 15)

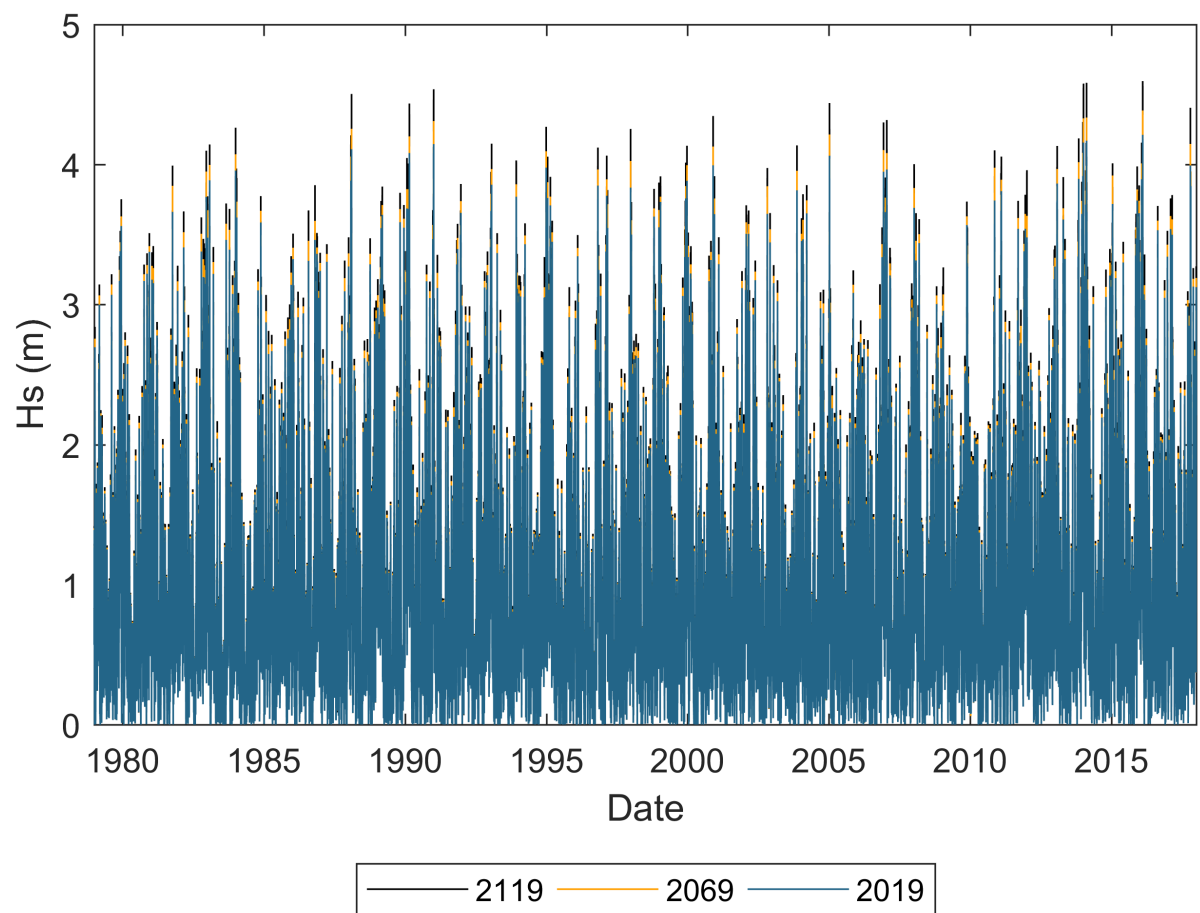


Figure 10. Time series of  $H_s$  at -7 mODN extraction point, epoch 2019

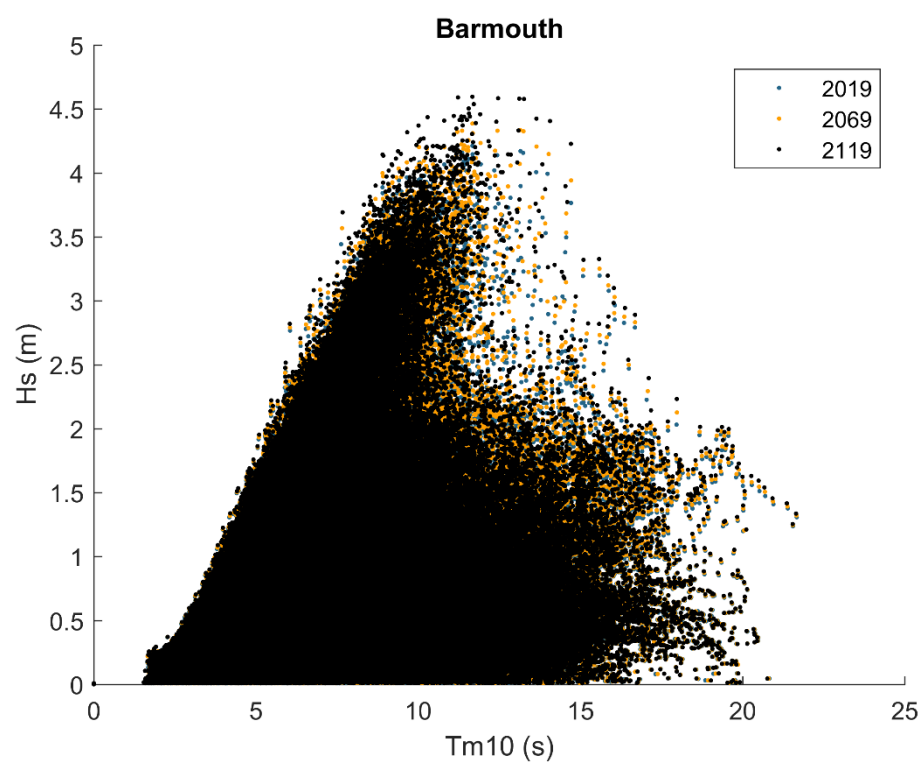


Figure 11. Scatter plot of  $H_s$  vs  $T_{m-1,0}$  at -7 mODN extraction point

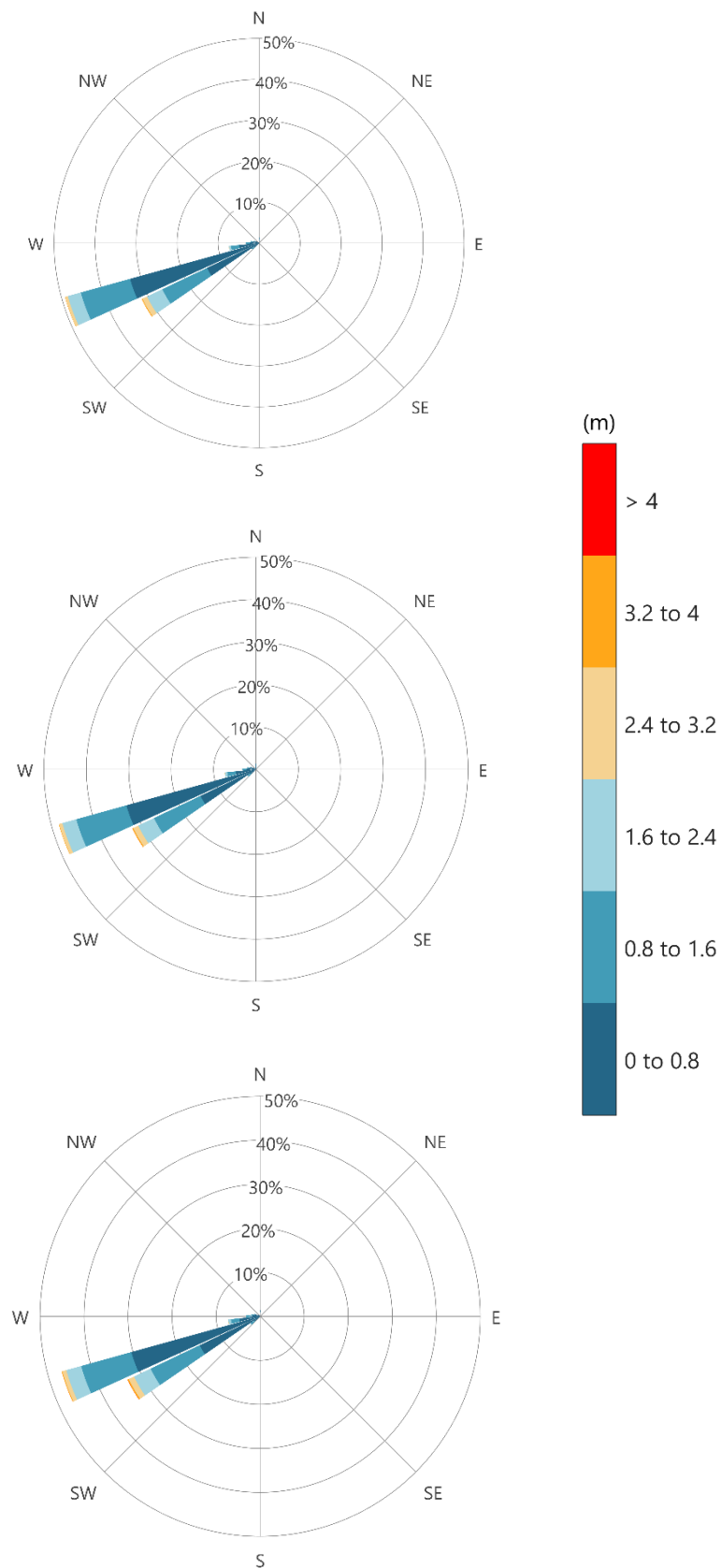


Figure 12. Wave roses showing Hs: epoch 2019 (upper), epoch 2069 (middle), epoch 2119 (lower)

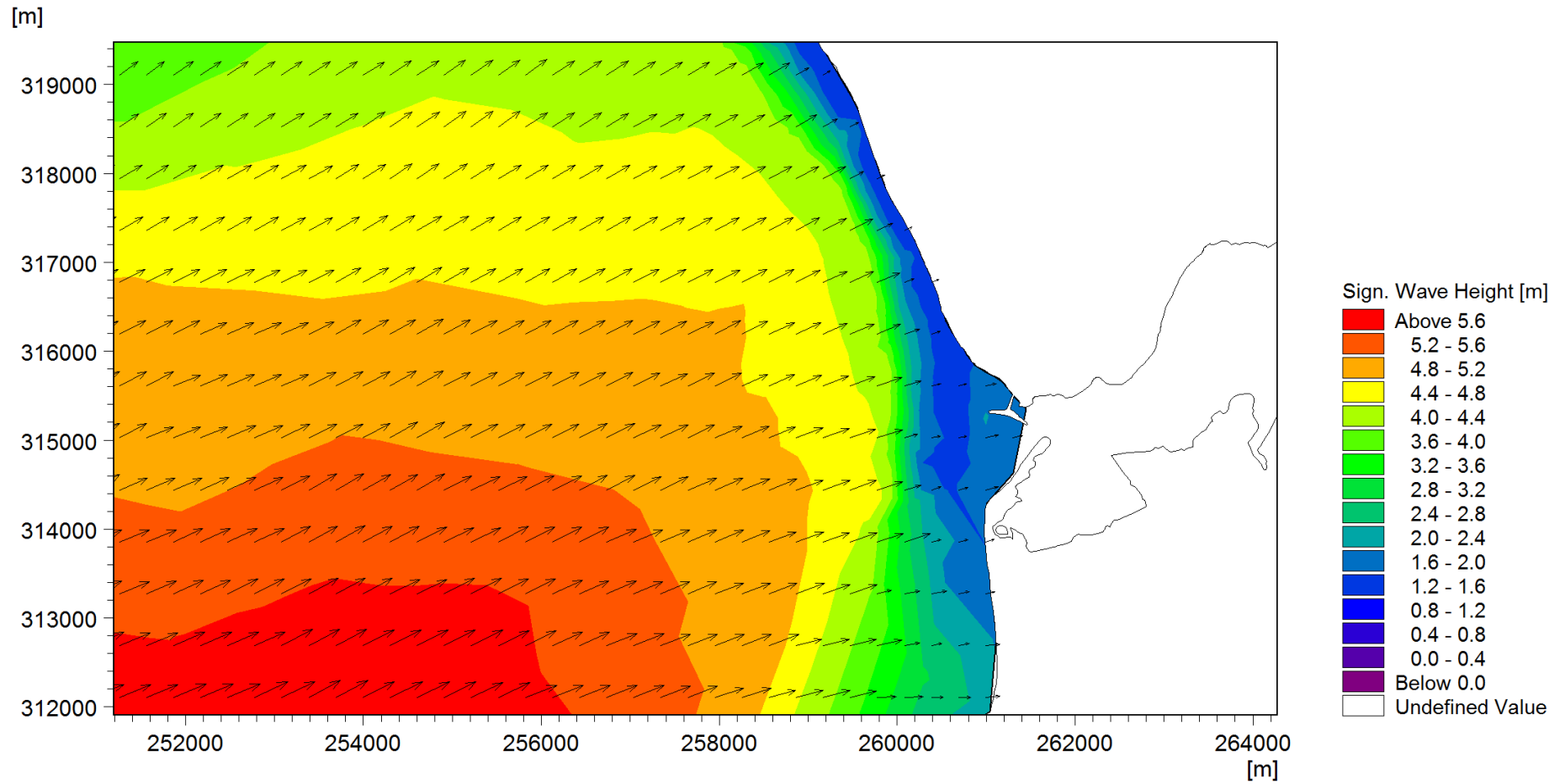


Figure 13. Map of significant wave height during February 2014 storm, epoch 2019<sup>1</sup>

<sup>1</sup> Barmouth harbour does not form part of the study and is therefore poorly resolved so wave growth in this area should be ignored.

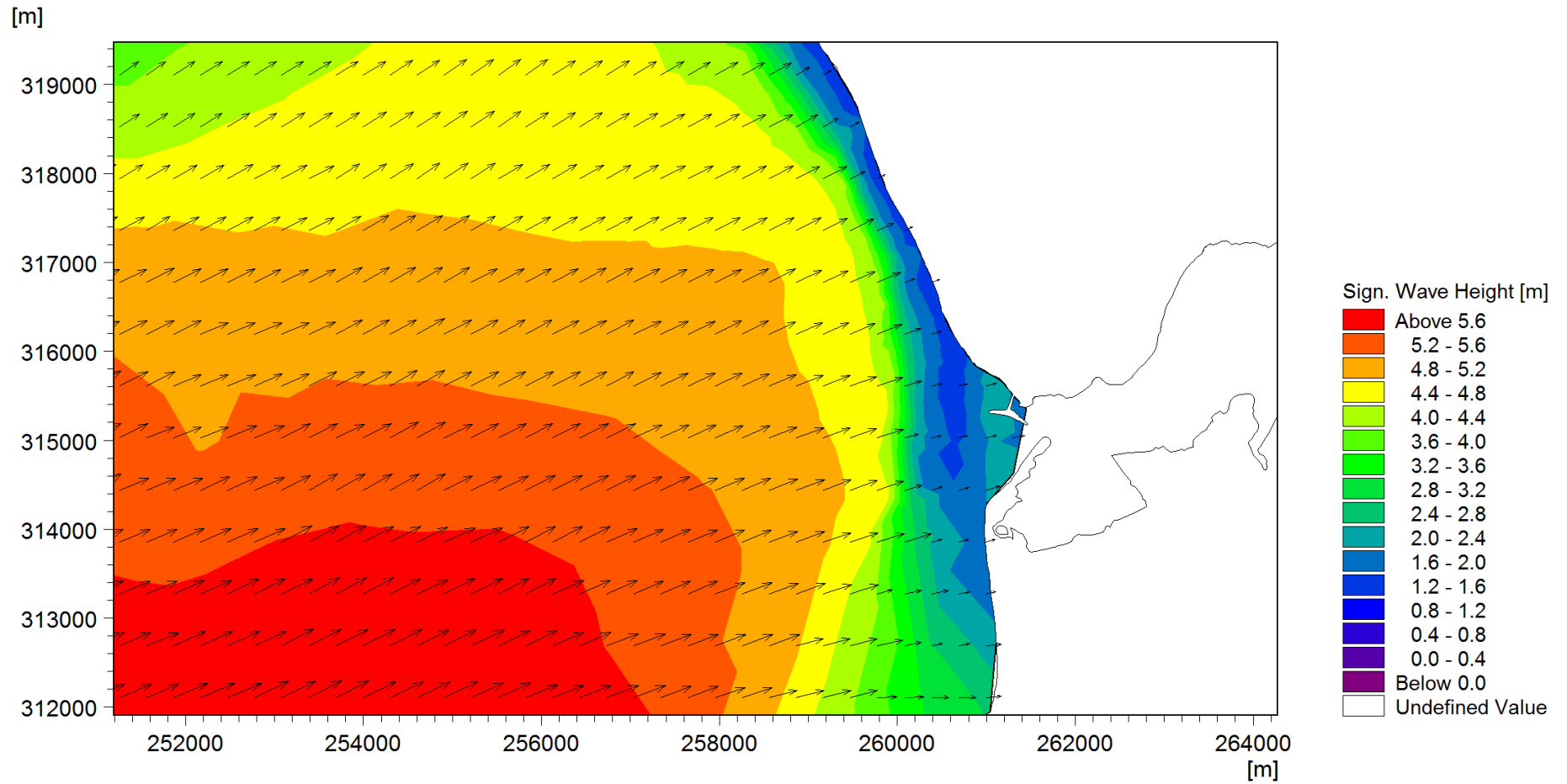


Figure 14. Map of significant wave height during February 2014 storm, epoch 2069

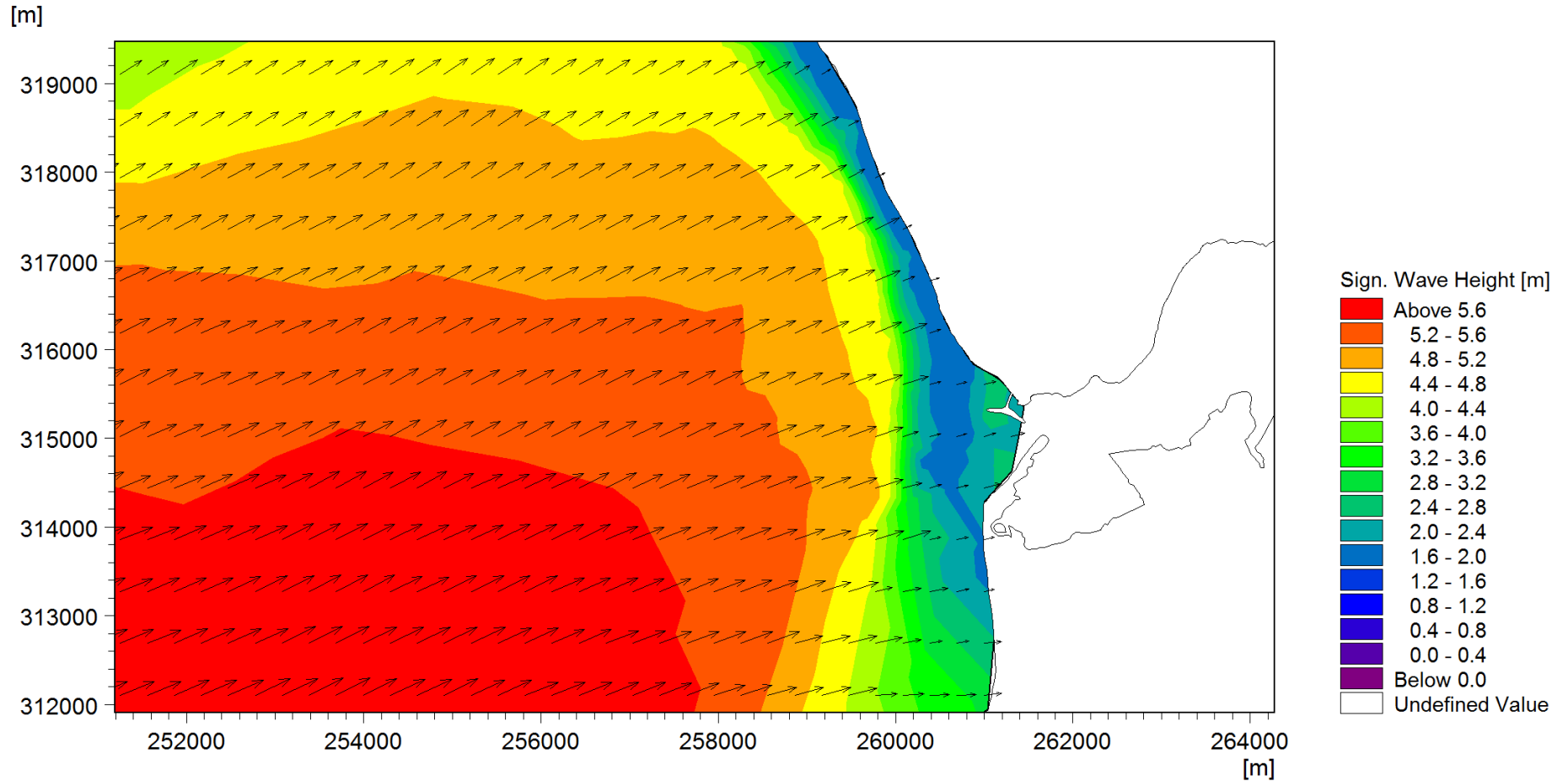


Figure 15. Map of significant wave height during February 2014 storm, epoch 2119

## 4 Extreme Value and Joint Probability Analysis

The 39 year hindcast timeseries of wave heights and water levels at the -7 mODN extraction location, for each of the three epochs (2019, 2069 and 2119) have been subject to Extreme Value Analysis (EVA) and Joint Probability Analysis (JPA).

The analysis has been carried out in two stages. Firstly, determination of the extreme water levels and wave heights as individual variables and secondly, the JPA. The methodology used in each stage is described in the following sections.

### 4.1 Extreme value analysis

Coastal flood risk at Barmouth is affected by incident wave conditions and water levels so it is important to derive estimates of extreme wave height and water levels at the different epochs, before exploring their relationship.

#### 4.1.1 Water level

In accordance with "Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities in Wales" (Welsh Government, 2017), the MRSLR has been added to extreme water levels derived from location data point 835 of the Environment Agency's (2011) Coastal Flood Boundary Dataset (CFBD), to provide extreme water levels for the relevant epochs.

#### 4.1.2 Significant wave height

Extreme wave heights have been determined based on the long-term wave hindcast data sets derived for a single location off the Barmouth frontage (Section 3) for the 2019, 2069 and 2119 epochs.

To ensure that each wave 'event' in the extremes analysis is statistically independent the wave height data were de-clustered. In this exercise, a single event was defined by wave height being above the threshold for a minimum of three hours, and a 24-hour interval was selected before a wave height reaching this threshold could be considered as another event.

The extremes analysis was then undertaken by fitting a Generalized Pareto Distribution (GPD) to the peak events. During this process, the storm events are further analysed using mean residual life plots which provide a suitable range of thresholds for the analysis. Shape and scale for this range of thresholds are plotted to identify the most suitable threshold value to be used in the final analysis. This standard checking process in GPD fitting helps to ensure that the GPD only utilises appropriate events that describe the extreme event population.

### 4.2 Joint Probability Analysis (JPA)

The aim of the JPA is to analyse the hindcast wave dataset created by the wave modelling in conjunction with long-term water levels to determine the correlation between large wave events and high-water levels. This correlation value is then used to predict pairings of wave and water level conditions of equal AEP. In this assessment water levels immediately off the site have been utilised from ABPmer's 39 years hindcast tide and surge model. This model provides a consistent set of water level data at the site over

the same period as the wave hindcast. The tide and surge model has been subject to extensive calibration (ABPmer, 2017)<sup>2</sup>.

The joint probability method used in this study is specified and described in the Defra/Environment Agency publication FD2308/TR2 (2005) and utilises the JOINSEA package developed by HR Wallingford. In this approach, a synthetic Monte Carlo simulation dataset is created which represents events that could occur over a much longer time frame than the 39 year record. This simulated data set possesses the same marginal return periods for wave heights and water levels, and the same level of correlation between these two variables, as the original source data.

From this synthetic dataset, the joint extreme period values of significant wave height and water level are extracted by a count-back procedure. Since the record of wave and water level events created by the Monte Carlo dataset is of a greater temporal length than the return periods of interest, a count-back procedure, rather than an extrapolation, is used to define the AEP of events. In accordance with FD2308/TR2 (2005), the analysis is undertaken at high water levels and the correlation used is that between significant wave height and high-water level.

The level of correlation between high water levels and high waves occurring at the same time will lie somewhere between -1 and 1, with 0 representing a situation where there is no dependence between the two variables (i.e. they are random and unrelated); 1 representing a situation of complete dependence (i.e. for high waves to occur, high water levels must also occur); and -1 representing a complete inverse dependence (i.e. as wave height increases, water level decreases).

The results of the JPA must be somewhere between these two situations, and 'sense check' tests have been performed by ensuring that the number of exceedances by the synthetic dataset of a given joint return period, lie between the expected number of exceedances for situations of complete dependence and complete independence. During the analysis, the dependence coefficient was 0.38, showing the two parameters are on the border of being 'modest/well' correlated, this is consistent with that suggested in FD2308/TR2 (2005), where the parameters are described to be 'well' correlated with a coefficient of 0.38 in the vicinity of the Fishguard.

In the JPA, the extreme water levels are then trained to closely replicate those derived from the Environment Agency's Coastal Flood Boundary Dataset and the extreme waves are trained to closely replicate those from the univariate extreme wave analysis results in Section 4.1.

#### 4.2.1 Derivation of associated wave periods

Wave period has been associated with wave and water level conditions in the Monte Carlo dataset using regression analysis based on wave steepness.

Figure 16 shows the three different relationships between  $H_s$  and Steepness, which depends on the wave height to water depth characterisation. For the hindcast data, most of the points are in the Intermediate category.

The fit of the linear regression model is shown in Figure 17, which shows the fit to be adequate. For the purposes of this analysis, the wave period used is the mean energy wave period,  $T_{m-1,0}$  (s), which is that used in the analysis of wave overtopping.

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<sup>2</sup> <http://www.seastates.net/downloads/>

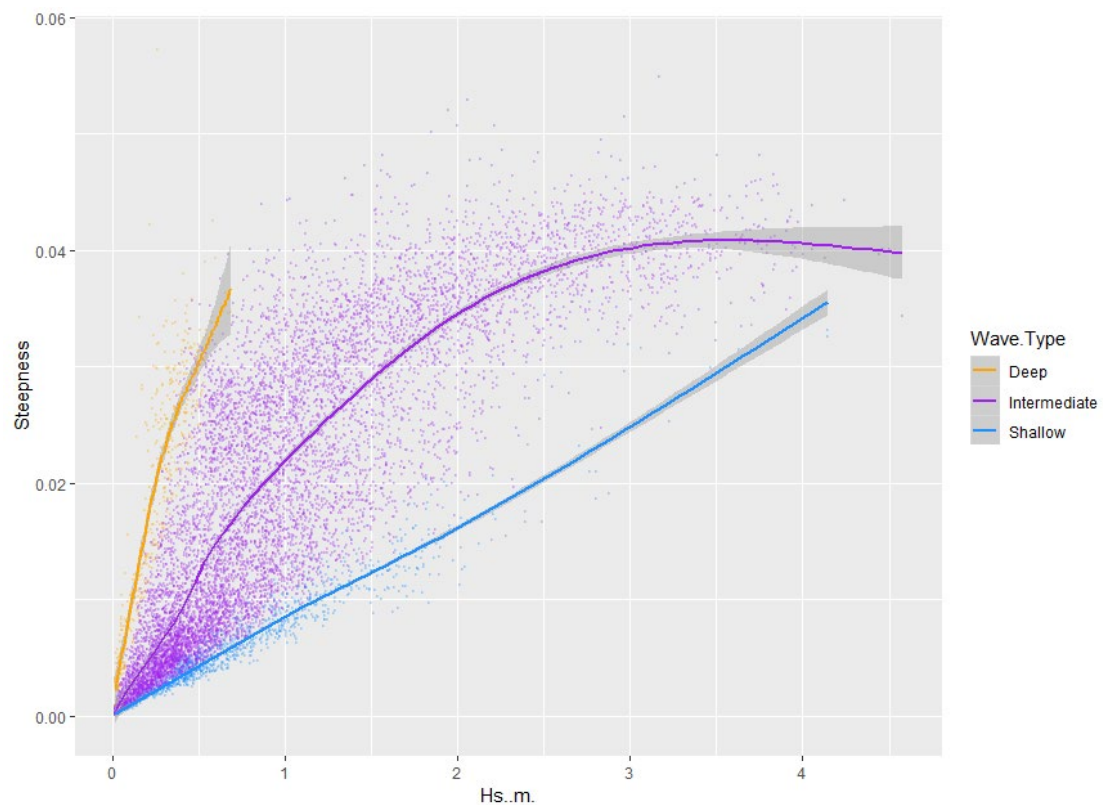


Figure 16. 2119 epoch: Relationship between Hs and wave steepness for three different wave types – Deep, Intermediate and shallow

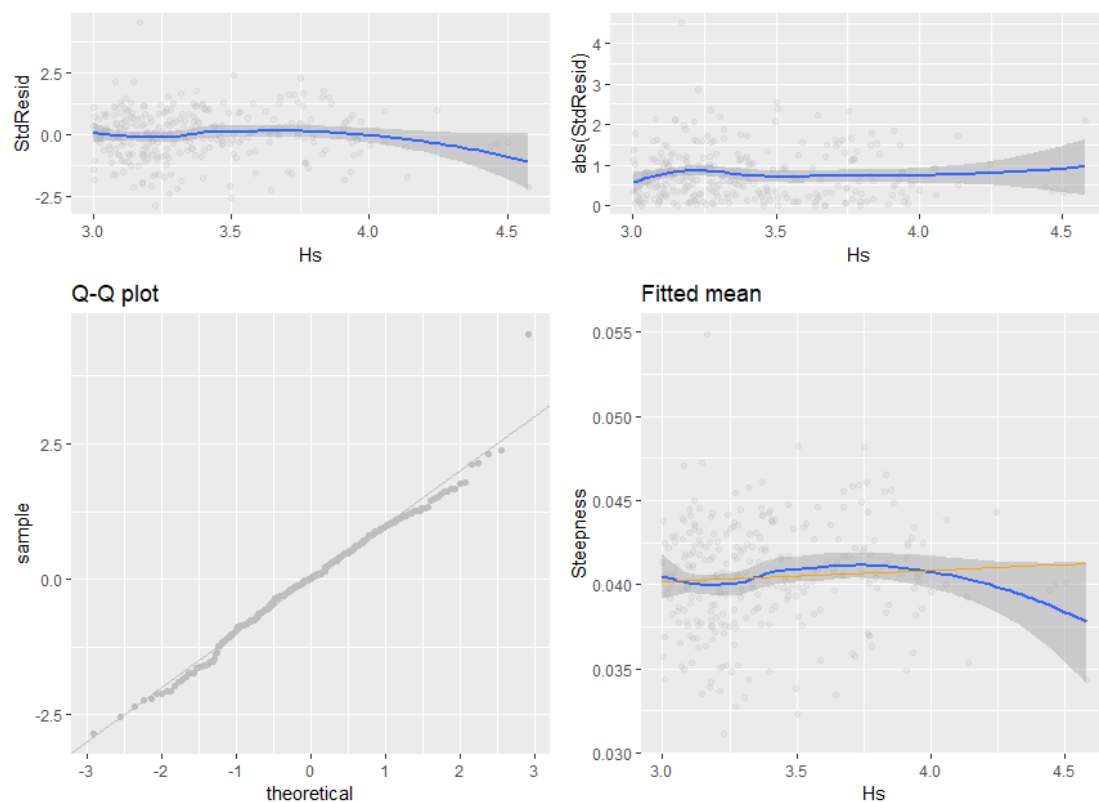


Figure 17. 2119 epoch: goodness of fit diagnostic plots for linear regression model for steepness given Hs

For each of the Monte Carlo events, values of wave steepness are generated given a value of  $H_s$  by simulating from a normal distribution with mean given by the fitted regression line, and variance equal to the variance of the model residuals. Once a value of steepness is obtained, the value of  $T_{m-1,0}$  (s) is found by satisfying the following equation:

$$\frac{H_s}{\text{Steepness}} = \frac{gT_{m-1,0}^2}{2\pi} \tanh(2\pi z_b \text{Steepness} / H_s)$$

where  $g = 9.8$ , and  $z_b$  (m) is water depth.

## 4.3 Results

The results of the EVA and the JPA are detailed in the following section.

### 4.3.1 Extreme water levels

Extreme water levels derived by adding MRSLR to CFBD data point 835 are shown in Table 3.

It is important to note that water levels should only be used to 1 d.p. They are presented to 2 d.p. to illustrate the differences between consecutive AEPs e.g. 1 % and 0.5 %.

**Table 3. Extreme water levels derived from CFBD 2008**

| Return Period | AEP (%) | CFBD (mODN) | Total Water Level (mODN) |            |            |
|---------------|---------|-------------|--------------------------|------------|------------|
|               |         | Epoch 2008  | Epoch 2019               | Epoch 2069 | Epoch 2119 |
| T1            | 100     | 3.48        | 3.52                     | 3.94       | 4.62       |
| T10           | 10      | 3.82        | 3.86                     | 4.28       | 4.96       |
| T50           | 2       | 4.03        | 4.07                     | 4.49       | 5.17       |
| T100          | 1       | 4.11        | 4.15                     | 4.57       | 5.25       |
| T200          | 0.5     | 4.20        | 4.24                     | 4.66       | 5.34       |
| T1000         | 0.1     | 4.39        | 4.43                     | 4.85       | 5.53       |

### 4.3.2 Extreme water levels sensitivity test

As per Welsh Government 2017, the CFBD 2008 dataset has been utilised in this study. During the study, draft data from the forthcoming revision (CFBD 2018) was provided by the client. CFBD 2018 predicts generally higher water levels at Barmouth than CFBD 2008 (Table 4).

**Table 4. Comparison of CFBD 2008 and CFBD 2018 at Barmouth**

| Return Period | AEP (%) | CFBD Base 2008 | CFBD Base 2018 |
|---------------|---------|----------------|----------------|
| T1            | 100     | 3.48           | 3.46           |
| T2            | 50      | 3.58           | 3.59           |
| T5            | 20      | 3.72           | 3.75           |
| T10           | 10      | 3.82           | 3.86           |
| T20           | 5       | 3.91           | 3.98           |
| T25           | 4       | 3.94           | 4.02           |
| T50           | 2       | 4.03           | 4.13           |
| T75           | 1.33    | 4.08           | 4.2            |

| Return Period | AEP (%) | CFBD Base 2008 | CFBD Base 2018 |
|---------------|---------|----------------|----------------|
| T100          | 1       | 4.11           | 4.25           |
| T150          | 0.667   | 4.16           | 4.32           |
| T200          | 0.5     | 4.20           | 4.37           |
| T250          | 0.4     | 4.23           | 4.41           |
| T300          | 0.33    | 4.25           | 4.44           |
| T500          | 0.2     | 4.31           | 4.53           |
| T1000         | 0.1     | 4.39           | 4.66           |
| T10000        | 0.01    | 4.66           | 5.08           |

For the 1:200 year return period, the CFBD 2018 predicts a water level 0.17 m higher than CFBD 2008. To help understand the effect of this increase in predicted water level, a sensitivity test has been undertaken on the 1:200 year epoch 2019 overtopping event.

The water level condition that resulted in the 1:200 year overtopping rate has been increased by 0.17 m, i.e. representing the increase predicted by CFBD 2018, and remodelled from the – 7 mODN contour.

In this case the result shows that the 1:200 year overtopping rate would expected to be around 20% higher if CFBD 2018 were used.

**Table 5. Results of CFBD 2018 sensitivity test**

| Water Level Increase | Hs at -7 mODN | Hs at Toe of Structure | WL   | Tm <sub>-1,0</sub> | Overtopping Rate (l/s/m) |
|----------------------|---------------|------------------------|------|--------------------|--------------------------|
| No Increase          | 3.62          | 2.7                    | 3.9  | 11.01              | 163                      |
| 0.17 m Increase      |               | 2.8                    | 4.07 |                    | 199                      |

### 4.3.3 Extreme significant wave height

Predicted extreme wave heights at the –7 mODN contour offshore of Barmouth frontage are presented in Table 6 and GPD fits for the three epochs are presented in Figure 18 to Figure 20.

It is important to note that wave heights should only be used to 1 d.p. They are presented to 2 d.p. to illustrate the differences between consecutive AEPs e.g. 1 % and 0.5 %.

**Table 6. Extreme significant wave height predictions at Barmouth frontage**

| Return Period | AEP (%) | Significant Wave Height (m) |            |            |
|---------------|---------|-----------------------------|------------|------------|
|               |         | Epoch 2019                  | Epoch 2069 | Epoch 2119 |
| T1            | 100     | 3.67                        | 3.78       | 3.92       |
| T10           | 10      | 4.12                        | 4.27       | 4.49       |
| T50           | 2       | 4.24                        | 4.41       | 4.67       |
| T100          | 1       | 4.27                        | 4.45       | 4.71       |
| T200          | 0.5     | 4.29                        | 4.47       | 4.75       |
| T1000         | 0.1     | 4.32                        | 4.51       | 4.80       |

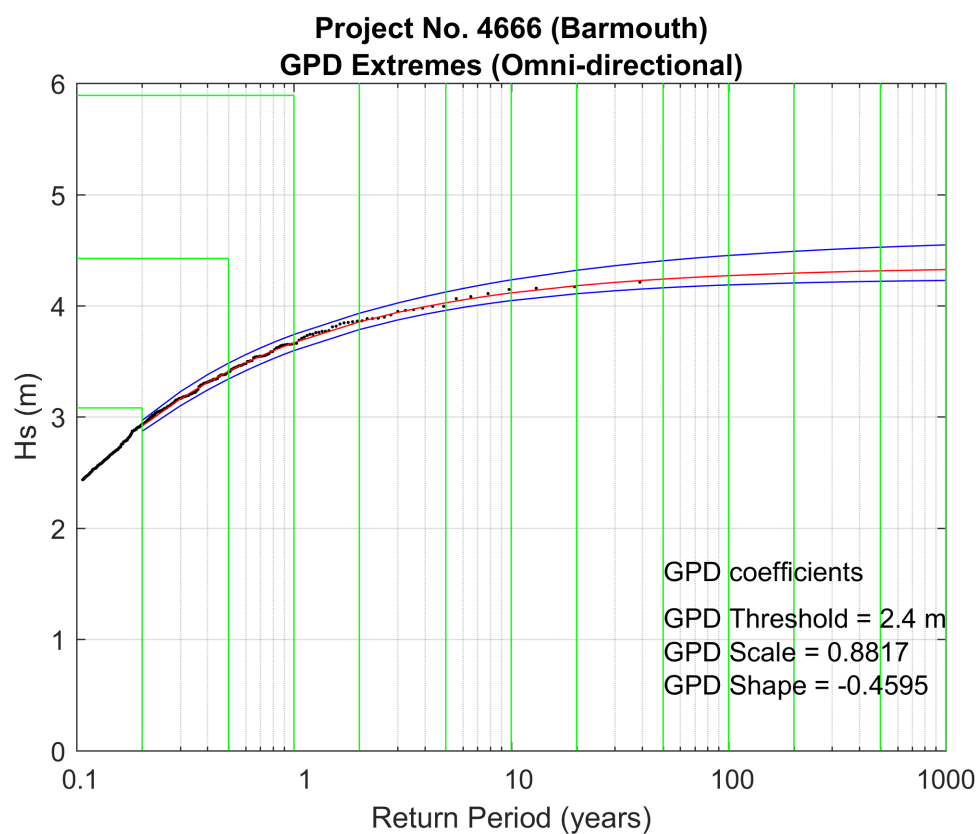


Figure 18. GPD fit of significant wave height, epoch 2019

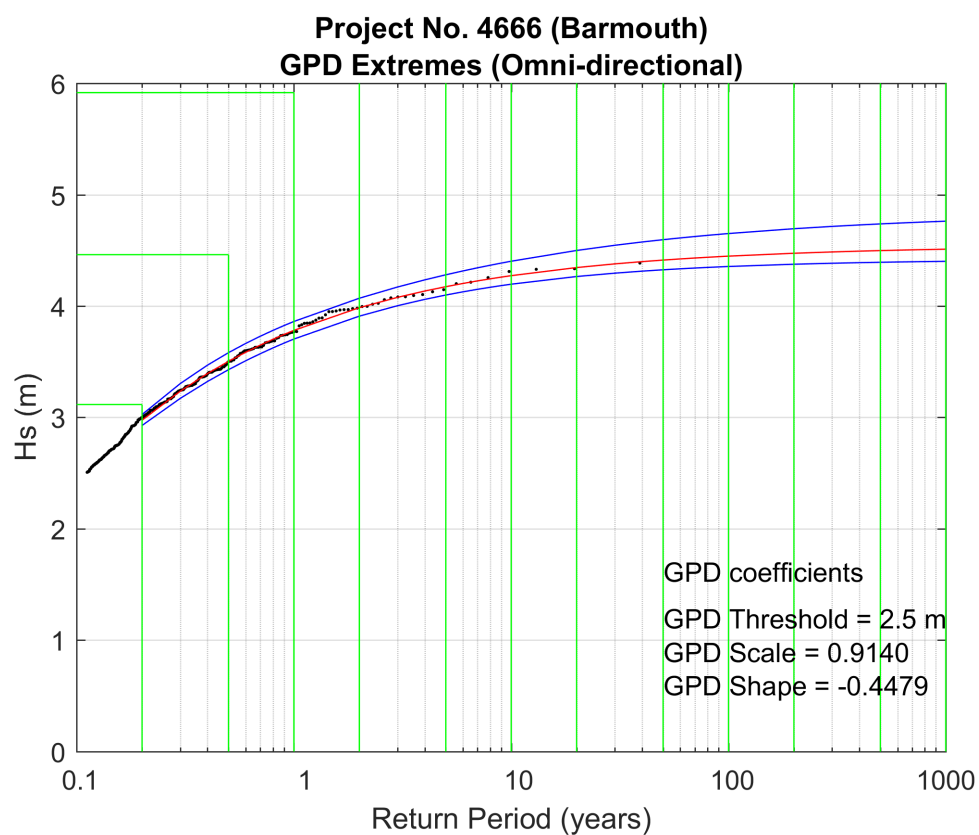


Figure 19. GPD fit of significant wave height, epoch 2069

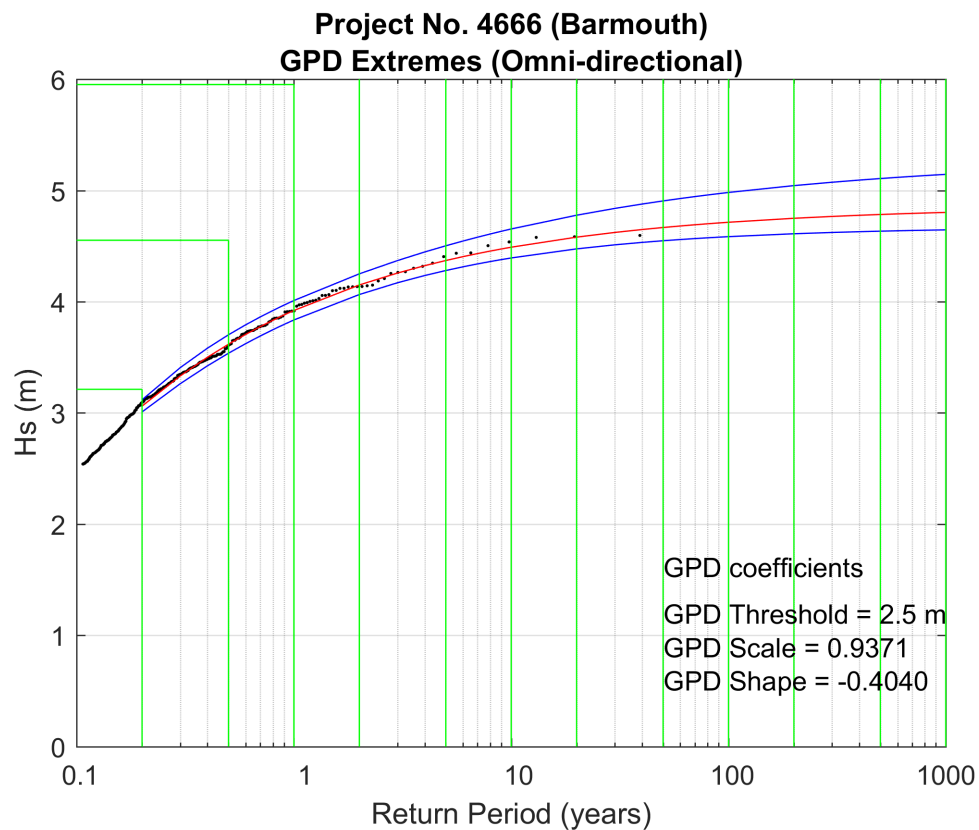


Figure 20. GPD fit of significant wave height, epoch 2119

#### 4.3.4 Joint probability wave and water levels

Joint probability contours of wave height and water level are presented in Figure 21 to Figure 23 and Table 7 provides the associated joint probability pairings. Only positive water levels (those above ODN) are shown on these plots. This is because the JPA is based on high water levels and large waves.

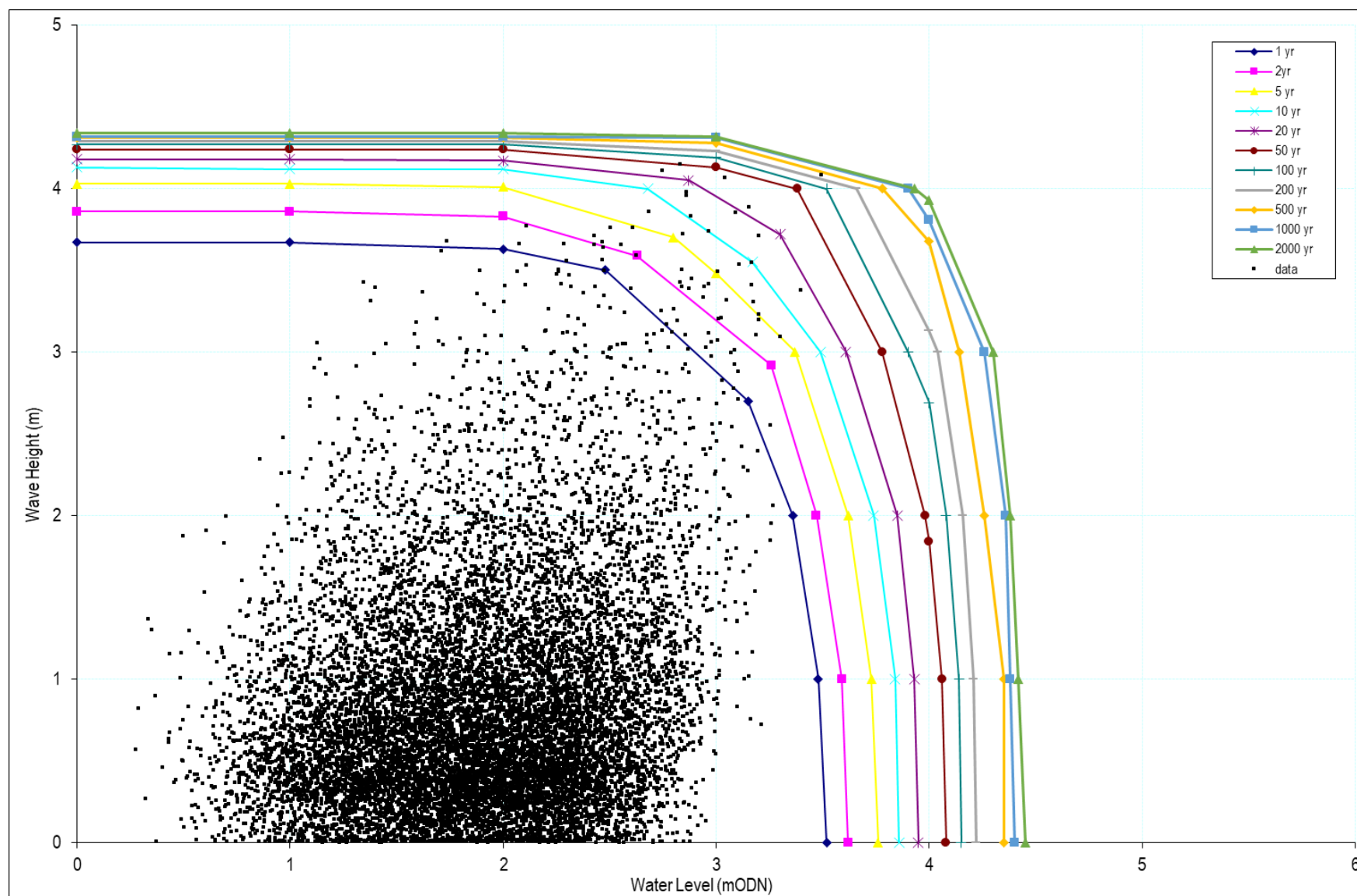


Figure 21. Joint Exceedance Curve at -7 mODN extraction location forced with CFBD extreme values, epoch 2019

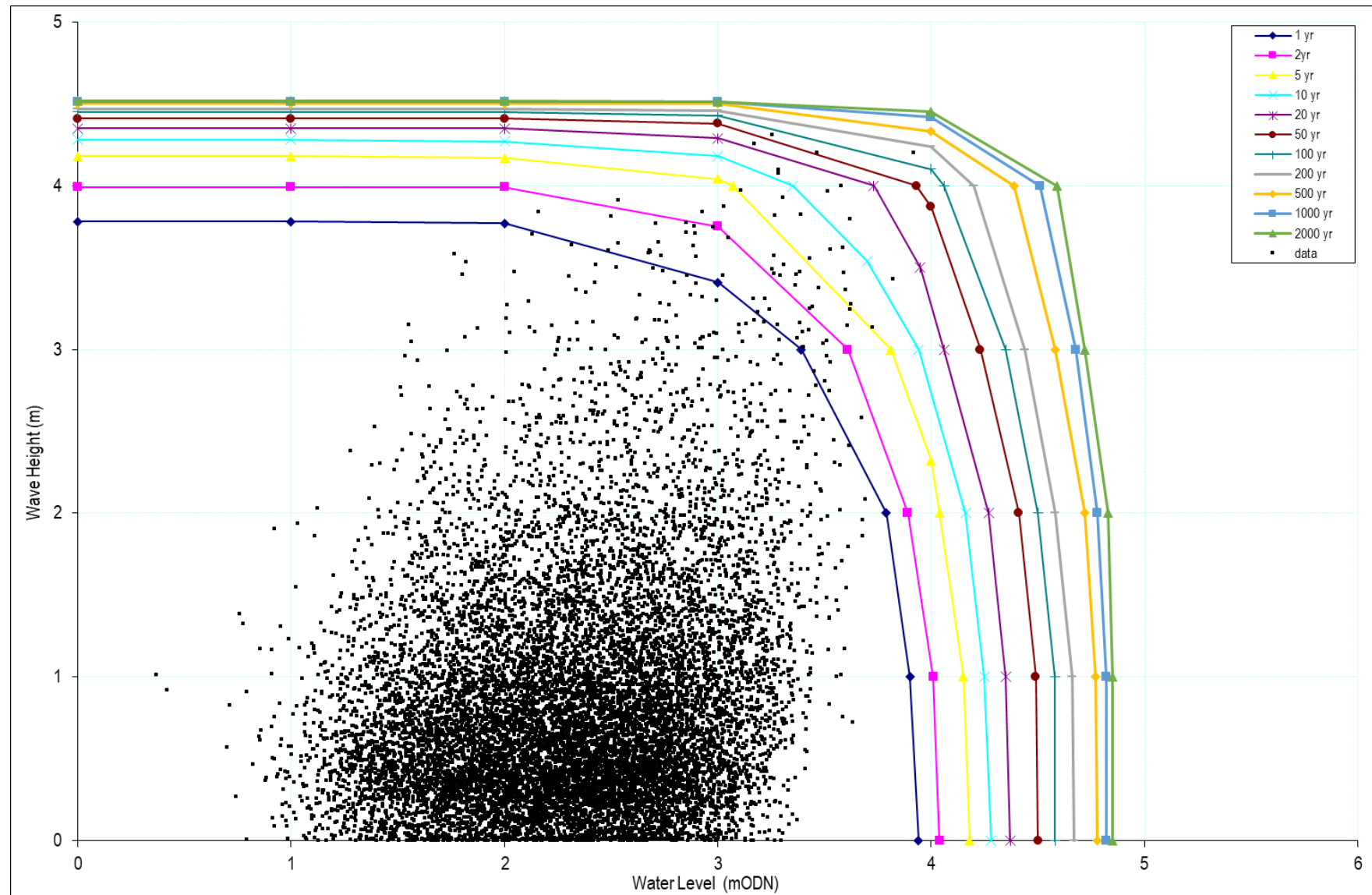


Figure 22. Joint Exceedance Curve at -7 mODN extraction location forced with CFBD extreme values, epoch 2069

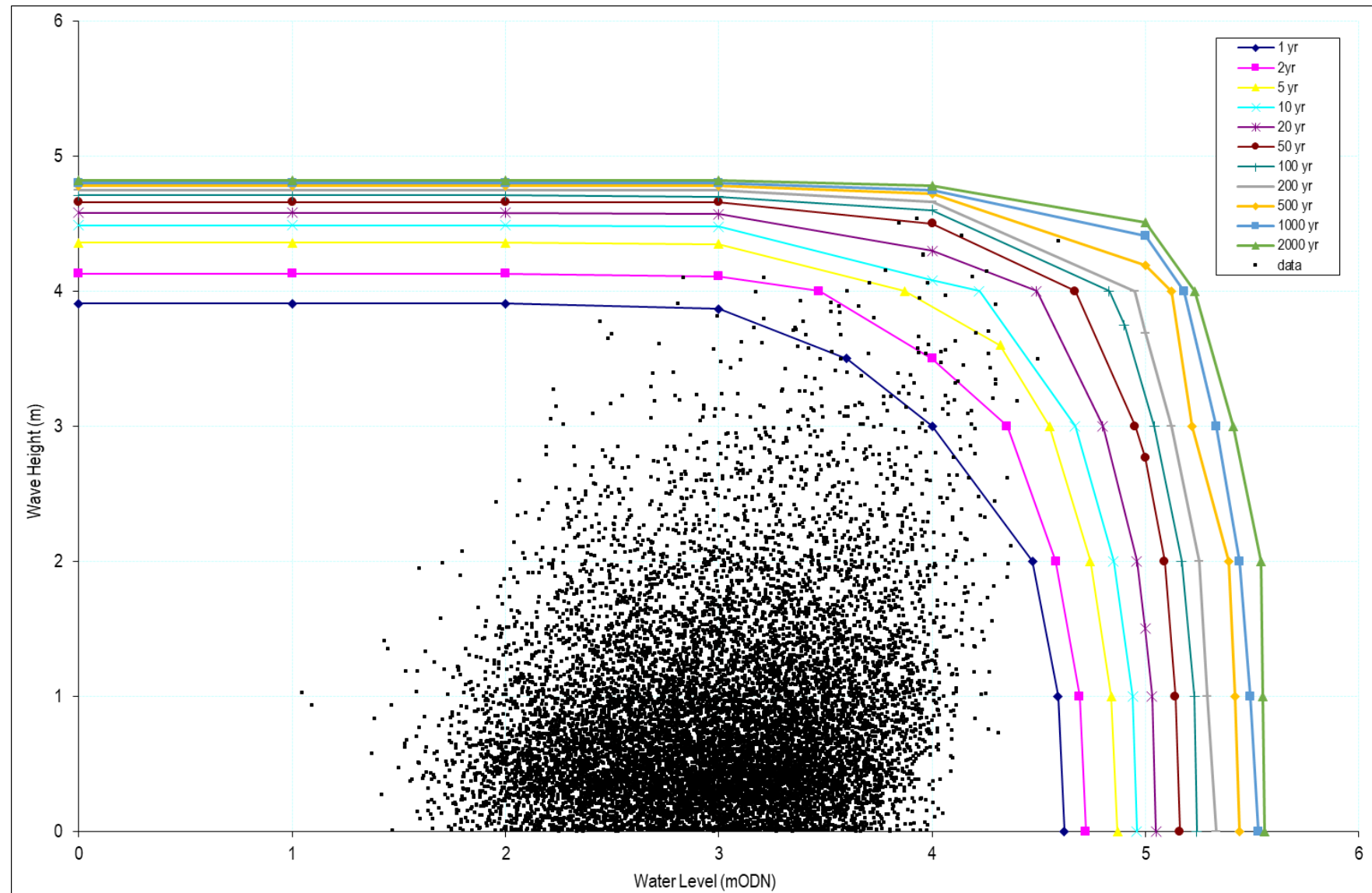


Figure 23. Joint Exceedance Curve at -7 mODN extraction location forced with CFBD extreme values, epoch 2119

**Table 7. Summary of joint exceedance at -7 mODN extraction location for epochs 2019, 2069 and 2119**

| Return Period | AEP (%) | Epoch 2019         |                             | Epoch 2069         |                             | Epoch 2119         |                             |
|---------------|---------|--------------------|-----------------------------|--------------------|-----------------------------|--------------------|-----------------------------|
|               |         | Water Level (mODN) | Significant Wave Height (m) | Water Level (mODN) | Significant Wave Height (m) | Water Level (mODN) | Significant Wave Height (m) |
| T1            | 100     | 1.0                | 3.7                         | 2.0                | 3.8                         | 3.0                | 3.9                         |
|               |         | 2.0                | 3.6                         | 3.0                | 3.4                         | 3.6                | 3.5                         |
|               |         | 2.5                | 3.5                         | 3.4                | 3.0                         | 4.0                | 3.0                         |
|               |         | 3.2                | 2.7                         | 3.8                | 2.0                         | 4.5                | 2.0                         |
|               |         | 3.4                | 2.0                         | 3.9                | 1.0                         | 4.6                | 1.0                         |
|               |         | 3.5                | 1.0                         | -                  | -                           | -                  | -                           |
| T10           | 10      | 2.0                | 4.1                         | 2.0                | 4.3                         | 3.0                | 4.5                         |
|               |         | 2.7                | 4.0                         | 3.0                | 4.2                         | 4.0                | 4.1                         |
|               |         | 3.2                | 3.6                         | 3.4                | 4.0                         | 4.2                | 4.0                         |
|               |         | 3.5                | 3.0                         | 3.7                | 3.5                         | 4.7                | 3.0                         |
|               |         | 3.7                | 2.0                         | 3.9                | 3.0                         | 4.9                | 2.0                         |
|               |         | 3.8                | 1.0                         | 4.2                | 2.0                         | -                  | -                           |
|               |         | -                  | -                           | 4.3                | 1.0                         | -                  | -                           |
| T50           | 2       | 2.0                | 4.2                         | 3.0                | 4.4                         | 3.0                | 4.7                         |
|               |         | 3.0                | 4.1                         | 3.9                | 4.0                         | 4.0                | 4.5                         |
|               |         | 3.4                | 4.0                         | 4.0                | 3.9                         | 4.7                | 4.0                         |
|               |         | 3.8                | 3.0                         | 4.2                | 3.0                         | 5.0                | 3.0                         |
|               |         | 4.0                | 2.0                         | 4.4                | 2.0                         | 5.1                | 2.0                         |
|               |         | 4.1                | 1.0                         | 4.5                | 1.0                         | -                  | -                           |
| T100          | 1       | 2.0                | 4.3                         | 2.0                | 4.5                         | 3.0                | 4.7                         |
|               |         | 3.0                | 4.2                         | 3.0                | 4.4                         | 4.0                | 4.6                         |
|               |         | 3.5                | 4.0                         | 4.0                | 4.1                         | 4.8                | 4.0                         |
|               |         | 3.9                | 3.0                         | 4.1                | 4.0                         | 4.9                | 3.8                         |
|               |         | 4.0                | 2.7                         | 4.4                | 3.0                         | 2.0                | 3.0                         |
|               |         | 4.1                | 2.0                         | 4.5                | 2.0                         | 5.2                | 2.0                         |
|               |         | -                  | -                           | 4.6                | 1.0                         | -                  | -                           |
| T200          | 0.5     | 2.0                | 4.3                         | 3.0                | 4.5                         | 3.0                | 4.8                         |
|               |         | 3.0                | 4.2                         | 4.0                | 4.2                         | 4.0                | 4.7                         |
|               |         | 3.7                | 4.0                         | 4.2                | 4.0                         | 5.0                | 4.0                         |
|               |         | 4.0                | 3.1                         | 4.4                | 3.0                         | 5.1                | 3.0                         |
|               |         | 4.2                | 2.0                         | 4.6                | 2.0                         | 5.3                | 2.0                         |
|               |         | -                  | -                           | 4.7                | 1.0                         | -                  | -                           |
| T1000         | 0.1     | 2.0                | 4.3                         | 3.0                | 4.5                         | 4.0                | 4.8                         |
|               |         | 3.9                | 4.0                         | 4.0                | 4.4                         | 5.0                | 4.4                         |
|               |         | 4.0                | 3.81                        | 4.5                | 4.0                         | 5.2                | 4.0                         |
|               |         | 4.3                | 3.0                         | 4.7                | 3.0                         | 5.3                | 3.0                         |
|               |         | 4.4                | 2.0                         | 4.8                | 2.0                         | 5.4                | 2.0                         |
|               |         | -                  | -                           | -                  | -                           | 5.5                | 1.0                         |

Caution should be taken when using the joint probability pairs and should not be used for design. This is because the associated AEP of any given response function (e.g. overtopping) is not directly related to the AEP of the wave and water level pairs for which the response function is calculated (Gouldby, 2017). Assigning a response function to an AEP based on a wave and water level pair is therefore known to result in the response function being underestimated. To avoid this issue, the Monte Carlo dataset has been used in the overtopping study.

#### 4.3.5 Associated wave period

For each wave and wave level condition in the Monte Carlo dataset wave period has been associated using a semi-parametric (statistical) model for wave steepness given  $H_s$ . A sample of the Monte Carlo data has been overlaid over the measured data in Figure 24. This shows that the distribution of wave height vs wave period in the Monte Carlo data set closely resembles that of the measured data.

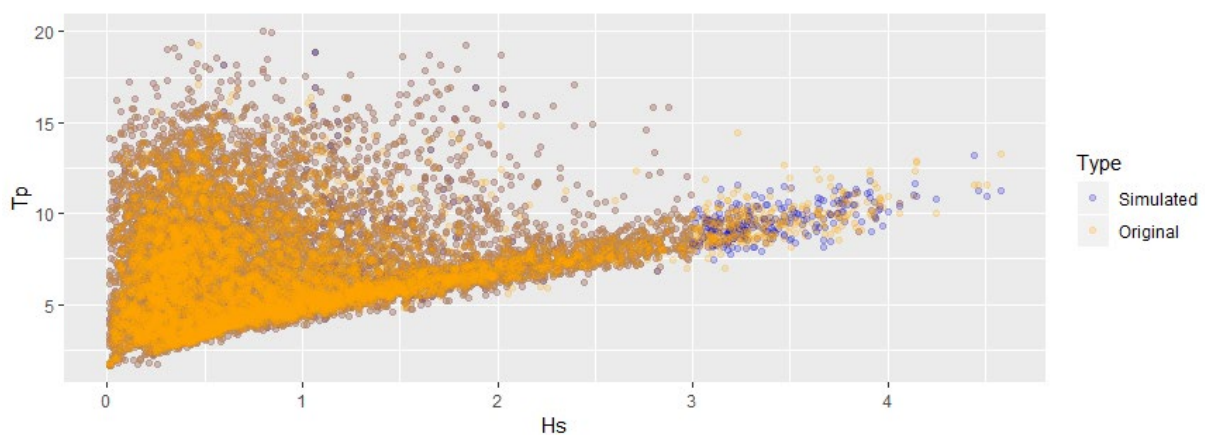


Figure 24. Scatter plot of significant wave height vs wave period for hindcast dataset (original) and synthetic Monte Carlo dataset (simulated)

## 5 Overtopping

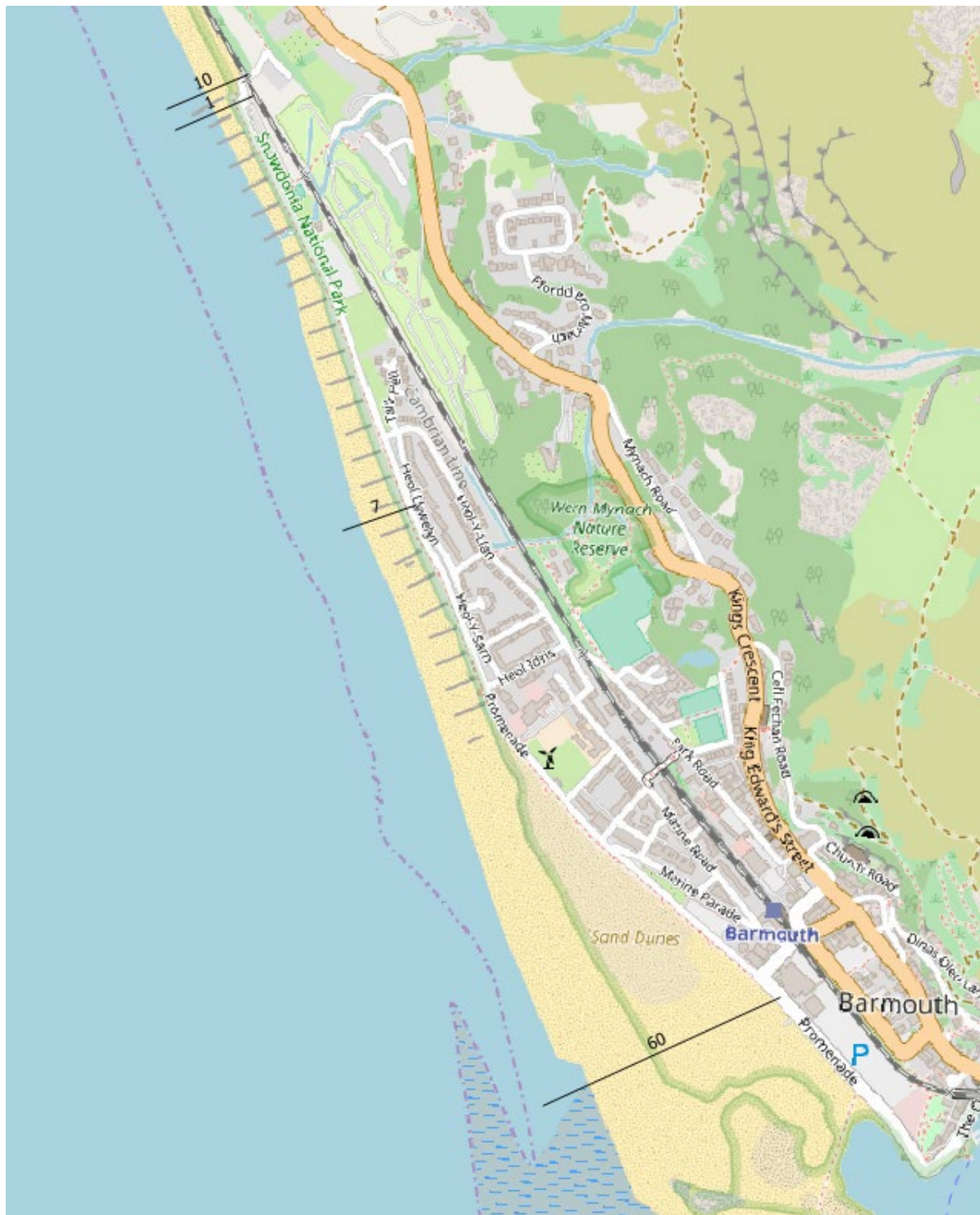
### 5.1 Methodology

#### 5.1.1 Introduction

The overtopping analysis has been undertaken in two parts, namely:

- Primary Analysis (Profile 1): The profile expected to result in the highest overtopping rates (Profile 1) has been subject to overtopping analysis for the full Monte Carlo set of events. This has been undertaken for the baseline case (present defence structure in 2019, 2069 and 2119, and for two alternate defence sections ('do nothing' and 'do something') for 2019, 2069 and 2119. This is referred as the primary analysis.
- Secondary Analysis (Profiles 7, 10 and 60): The remaining three profiles have used events derived from the Profile 1 Monte Carlo dataset and are subject to more limited analyses to examine how overtopping rates are expected to differ at Profile 7, 10 and 60. These have been undertaken for the baseline case (present defence structure) for 2019, 2069 and 2119. An alternative defence section ('do something') has also been tested for Profile 7. This is referred as the secondary analysis.

The locations of these profiles are shown in Figure 25 whilst the profiles are shown in Figure 26. The analyses are described in the following sections.



**Figure 25.** Location of cross-shore profiles (© OpenStreetMap contributors)

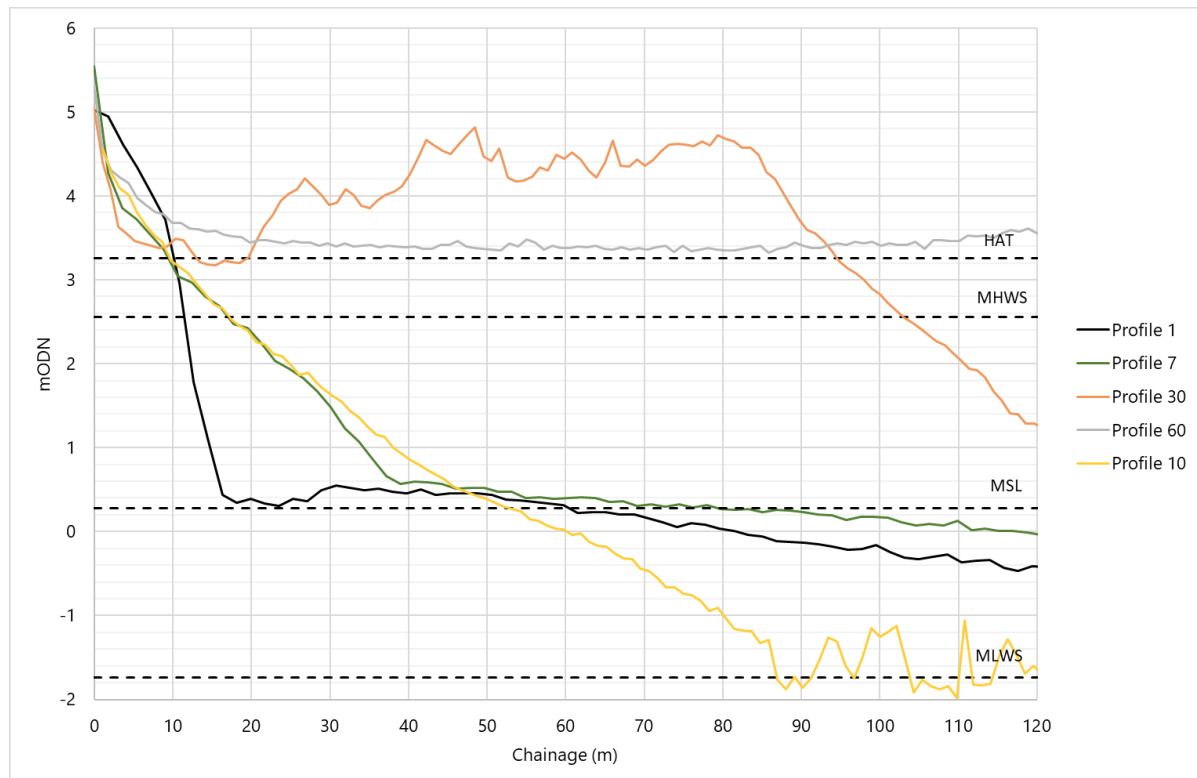


Figure 26. Cross-shore profiles from the composite DSM<sup>3</sup> (Profile 30 is also included on this figure for reference. This profile is discussed in section 5.4.4)

### 5.1.2 Primary analysis methodology (Profile 1)

Wave and water level conditions from the synthetic Monte Carlo dataset have been used to predict overtopping rates at Profile 1, at the northern end of Barmouth North Promenade (Figure 25). Profile 1 was selected as the primary section of interest as the bed level at the toe of the defence is lowest at this location and therefore, Profile 1 is likely to be subjected to the highest overtopping rates.

In this assessment, the full Monte Carlo dataset (equivalent to 10,000 years of events) was transformed inshore and then run through the overtopping Neural Network Tool (NNT) developed under EurOtop (2007) methodology. The EurOtop 2007 version has been chosen for this study as EurOtop 2018 only allows a small number of events to be modelled and therefore is not suitable for Monte Carlo analysis.

To undertake the overtopping assessment the following processes were completed:

- For each wave and water level condition from the Monte Carlo dataset, wave conditions were transformed inshore from the -7 mODN extraction location to the toe of the defence structure using DHI's 1D Litdrift model.
- Resulting wave conditions at the toe of the structure were extracted and used as inputs to the Neural Network Tool (NNT) to give predictions of overtopping rates.
- From this resulting dataset, a count-back approach was applied to derive overtopping rates for the following AEPs: 100%, 10%, 2%, 1%, 0.5% and 0.1%.
- This was completed for all epochs (2019, 2069 and 2119) for baseline case, 'do nothing' and 'do something' scenarios.

<sup>3</sup> The composite DSM contains LiDAR data flown on different dates and therefore the profiles shown in Figure 26 are representative of different dates (<http://lle.gov.wales>)

### 5.1.3 Secondary analysis methodology (Profiles 7, 10 and 60)

As introduced above, the remaining three profiles have used events derived from the Monte Carlo dataset from Profile 1 and were subject to more limited analyses to examine how overtopping rates are expected to differ at these locations. The additional profiles examined are:

- Profile 7 - the southern section of North Promenade where the bed level at the toe of the structure is higher;
- Profile 10 - the shingle ridge to the north of the promenade; and
- Profile 60 - the beach at Barmouth South

The overtopping AEP defined in section 5.1.2 above is specific to profile 1 (because it has been derived from the location specific Monte Carlo analysis). However, the wave and water level pairings which resulted in the overtopping AEP will be broadly comparable to the other profiles along the frontage. To understand how the base case overtopping AEP will differ at Profiles 7, 10 and 60, the project has examined the associated wave and water level pairings. For each Monte Carlo AEP (derived by the count-back in section 5.1.2 above) the equivalent wave and water level pairing has been identified. The adjacent 5 pairings above and below have also been identified, a total of 11 pairings for analysis for each AEP (hereon referred as 'The Pairings').

It should be noted that actual overtopping rates at any given location will be sensitive to a range of parameters including wave and water level characteristics, shoreline topography and scheme representation in the NNT. This method is considered appropriate for considering differences in overtopping between profiles and schemes for OBC. However, any scheme development post OBC should be supported by full Monte Carlo analysis or equivalent.

For these profiles, the processes completed were as follows:

- Baseline (Profiles 7, 10, 60): For each epoch and AEP, The Pairings were transformed inshore using Litdrift;
- Do Something (Profile 7): For each epoch and AEP, The Pairings for an alternative defence configuration ('do something') were transformed inshore using Litdrift;
- The results were extracted and run through the NNT; and
- The overtopping rates from The Pairings were then averaged to provide an associated overtopping rate for each epoch and AEP.

### 5.1.4 Limitations of EurOtop neural network tool

The results tables in section 5.3.2 and 5.3.2 provide overtopping rates (and Associated Overtopping) for most of the cases. However, for the later epochs and small AEP's (more extreme events) no overtopping results are presented. This is because the cases being examined are very extreme, and the scenarios lie outside of the test data that underpins the EurOtop NNT. This is expected, because in some cases, for example the 'Do Nothing' scenario, individual wave and water level events can be very large in respect to the crest level of the defence are being tested. This is particularly the case for the latter epochs, where there are many instances when the Still Water Level (**SWL**) is above the Defence Crest Level (**DCL**). These are conditions which would not generally be designed for and hence are not covered by the physical model test data that informs the EurOtop NNT. Hence a null value may be returned for an individual event, even though overtopping would be expected.

From an examination of the 'do-nothing' results the following categories were generally found to relate in a null value being returned from the NNT, when overtopping would still be expected:

- **Category A null:**  $SWL > DCL$
- **Category B null:**  $SWL + 0.5 \cdot H_s > DCL$
- **Category C null:**  $SWL + 0.5 \cdot H_s < DCL$ ; but 'wave freeboard' defined as  $DCL - (SWL + 0.5 \cdot H_s)$  is small and wave period is large (typically  $> 15$  sec)

The vast majority of the events that returned a null value, when overtopping is expected, were from Category A or B. These events would be expected to result in very significant overtopping. The very limited number of events from Category C, included events, that may have resulted in some more limited overtopping.

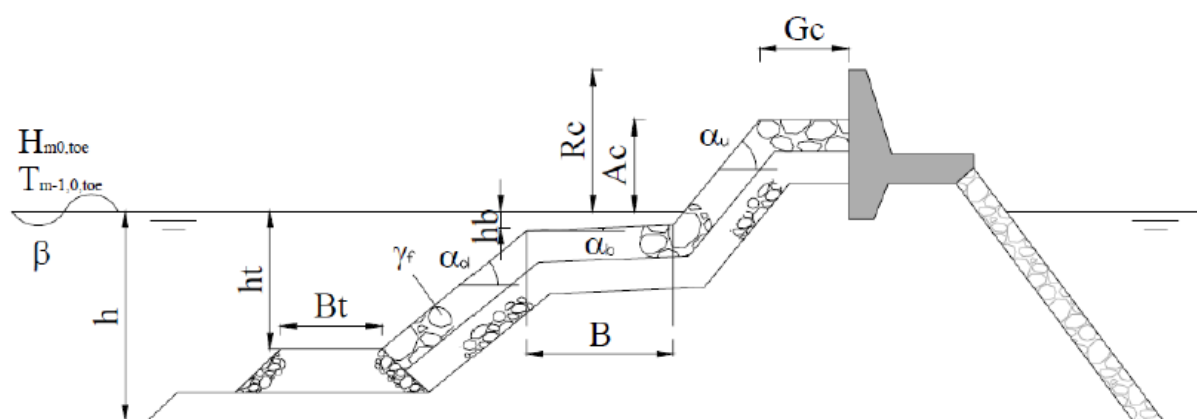
Therefore, when undertaking the count-back approach, events that were in Category A or Category B, were ranked to have had greater overtopping than events that returned a valid overtopping rate. The limited number of Category C events were ignored when undertaking the count-back approach, since the overtopping expected with these events was often much lower. Because of the limited number of these events, the effect of ignoring these events in the count-back assessment is minimal.

Where null values are returned from Category A or B events for all events that are more extreme than the AEP being examined, it is not possible to provide an associated overtopping rate for that AEP and a null value is assigned in the results tables.

Where a null value is assigned for the base case for a given epoch / AEP condition, it has not been possible to associate wave and water level events with the overtopping rate for that epoch/AEP condition. In these cases, it has not been possible to assess the overtopping rate for the secondary profiles, and the phrase 'no associated event available' is found in the results tables.

## 5.2 Schematisation of defence sections

Within the NNT defences are schematised using 15 geometric parameters which include; crest height ( $R_c$ ), armour height ( $A_c$ ), armour width ( $G_c$ ), berm elevation ( $h_b$ ), berm width ( $B$ ), upper slope ( $\alpha_u$ ), lower slope ( $\alpha_d$ ) and roughness ( $\gamma_i$ ) (See Figure 27).



Source: Coeveld *et al*, 2005: CLASH Database

**Figure 27.** Schematisation descriptors for a defence profile using neural networks overtopping tool

Each of the four defence sections were schematised into the NNT using these 15 parameters. The topographic survey data from 2018 was used to select the crest height and the 2016 UAV data was used alongside 1 m resolution LiDAR data to schematise the defence seaward of the crest. The defence schematisations are presented in Sections 5.2.1 to 5.2.4.

**Accounting for bed level change for future epoch scenarios:** The associated coastal process review (ABPmer, 2019) has identified that bed levels have historically been lowering along Barmouth North Promenade and that this bed lowering is expected to continue into the future. Therefore, for Profiles 1, 7 and 10, the bed level at the toe of the defences has been lowered when assessing overtopping for future epochs. The bed lowering applied is as per the predicted bed lowering identified in ABPmer, 2019. No bed lowering was applied to Profile 60, since bed levels have historically been rising in this area.

### 5.2.1 Northern section of North Promenade (Profile 1)

#### Base case

The northern section of the promenade consists of a vertical sheet piled sea wall, a concrete platform, stone blockwork revetment and precast concrete wave recurve wall units (Figure 28). The base case schematisation of this defence section is shown in Figure 29.



Photograph: Arup, 2018

Figure 28. Photograph of coastal defence (Profile 1)

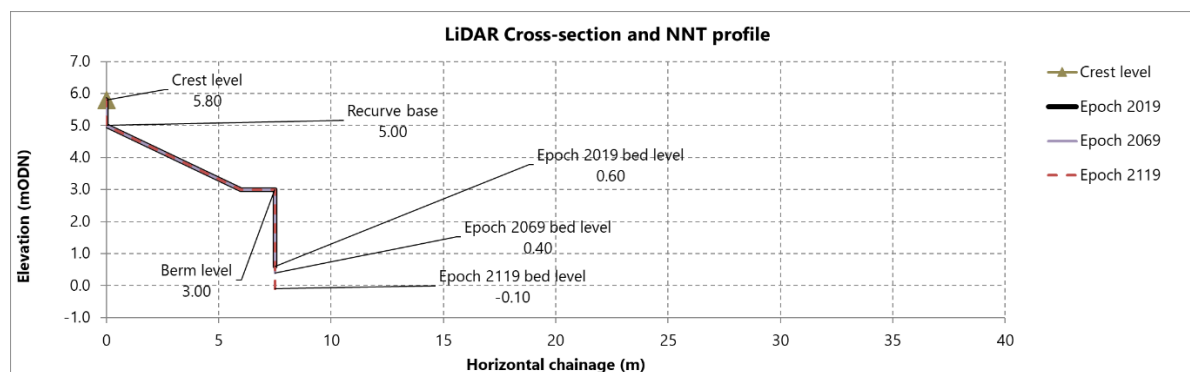


Figure 29. Profile 1: Base Case

### Do Nothing: Primary Wall Failure

A complete failure of the primary wall, representing a worst credible case, as shown in Figure 30.

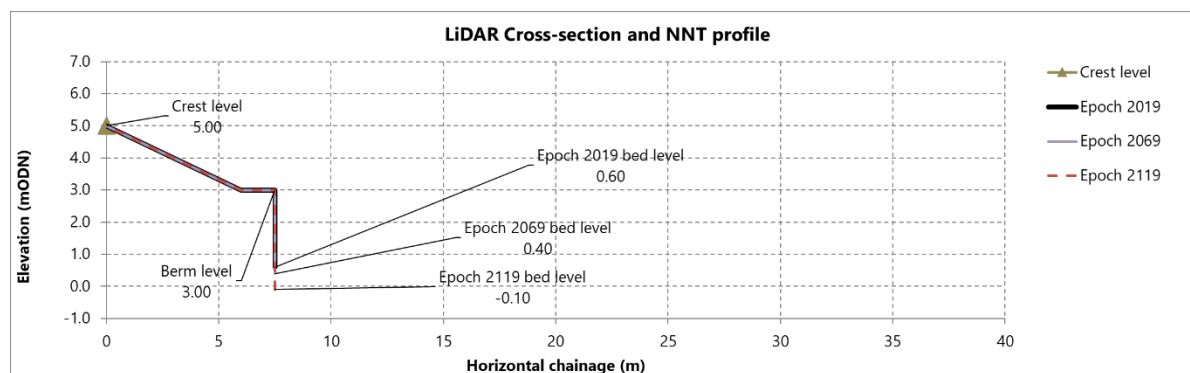


Figure 30. Profile 1: Do nothing

### Do Something: Rock Toe and Increased Crest Height

New rock toe and increased crest height on the primary wall has been tested. The crest height has been tested at 6 m, 6.25 m and 7 m.

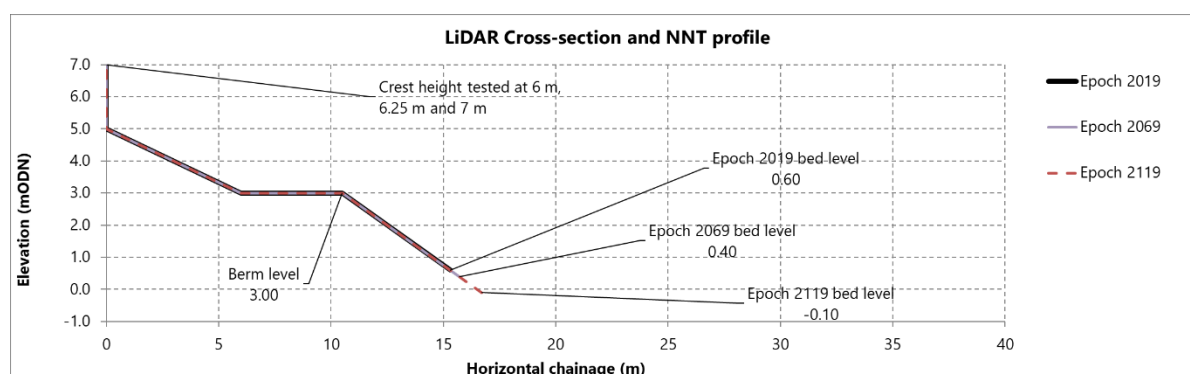


Figure 31. Profile 1: Do something

## 5.2.2 Southern section of North Promenade (Profile 7)

The southern section of the promenade has been subject to less beach lowering than the northern section and hence has a higher beach level against the vertical sheet piled sea wall. The schematisation of the southern section of the promenade is shown in Figure 33.



Photograph: Arup, 2018

Figure 32. Photograph of southern section of promenade

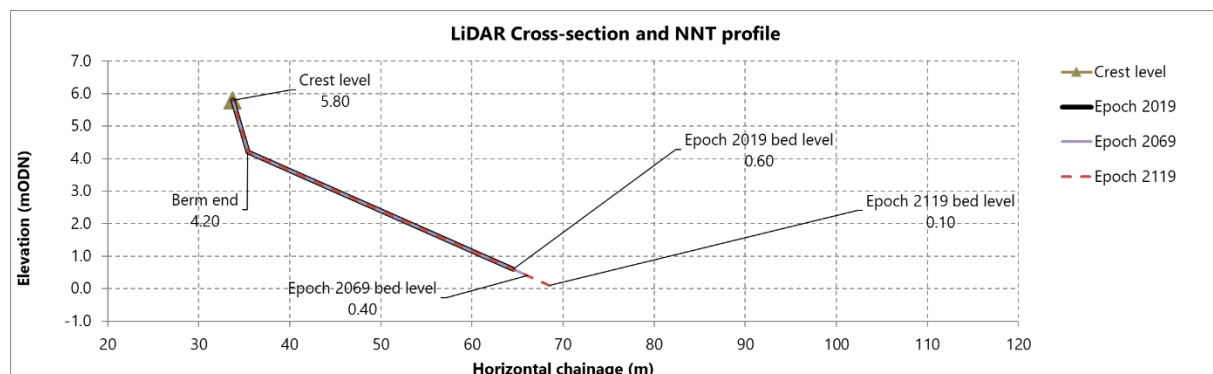


Figure 33. Profile 7: Base Case

### Do Something: Shingle beach and increased crest height

At the southern section of the promenade, a scheme with a shingle beach and increased crest height on the primary wall has been tested. The shingle beach has been represented by a 1 in 10 slope.

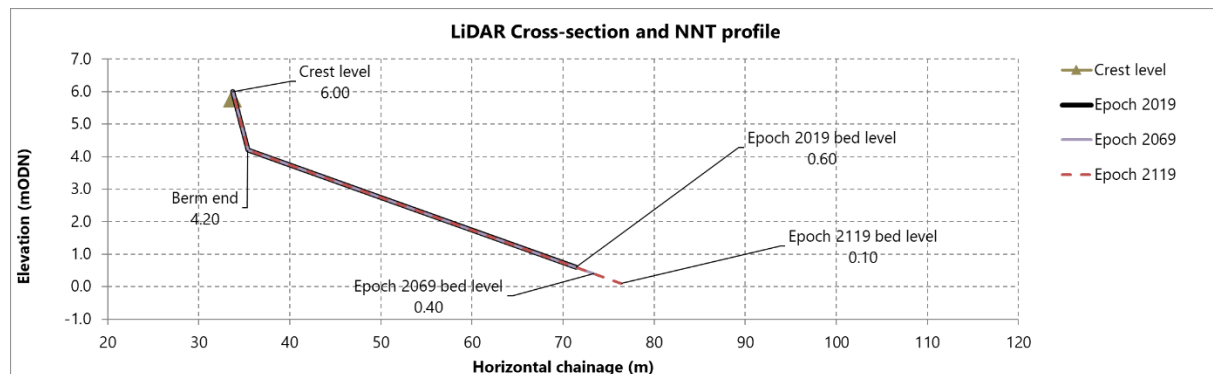


Figure 34. Profile 7: Do something

### 5.2.3 Shingle Ridge to north of North Promenade (Profile 10)

The shingle ridge to the north of the promenade is shown in Figure 35. A schematisation of this ridge is shown in Figure 36. The levels used to develop this schematisation are based on Natural Resources Wales' composite LiDAR data which was mainly made up from the latest survey in 2014 (<http://lle.gov.wales/>). A 1 in 8 slope has been used to represent the beach profile.

It is important to note that NNT is designed to be used for solid structures rather than natural defence structures such as mobile shingle banks. A roughness value of 0.8 has been applied to the model to capture some of the shingle banks ability to absorb wave energy.



Photograph: Arup, 2018

Figure 35. Photograph of shingle ridge (north of North Promenade)

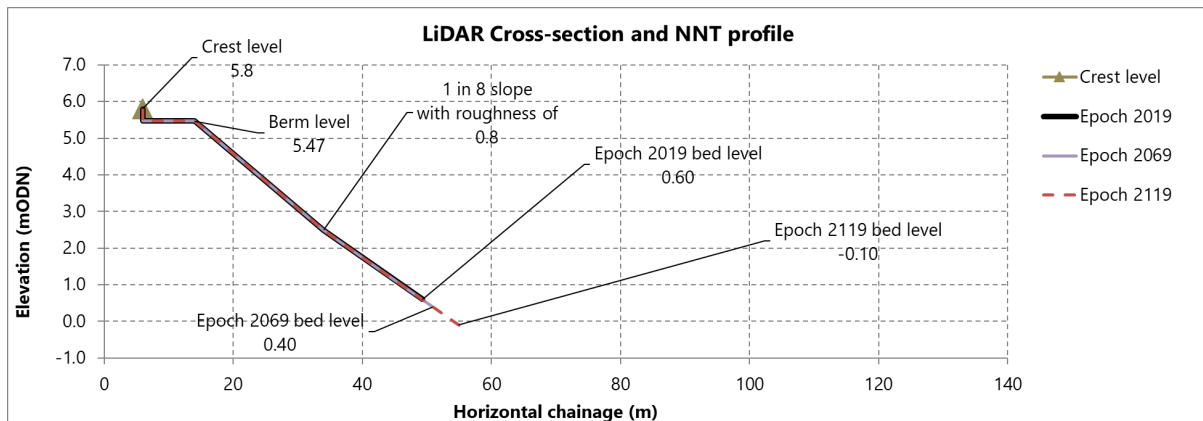


Figure 36. Profile 10: Base Case

## 5.2.4 Barmouth South (Profile 60)

A large beach with dynamic foredunes and embryo dunes lies to the south of Barmouth North Promenade. The dunes offer protection against flooding in the present epoch but there is an area (around profile 60) where dunes are not present and hence flood risk is higher (Figure 37). The schematisation for Barmouth South is shown in Figure 38.



Figure 37. Aerial photograph of Barmouth South

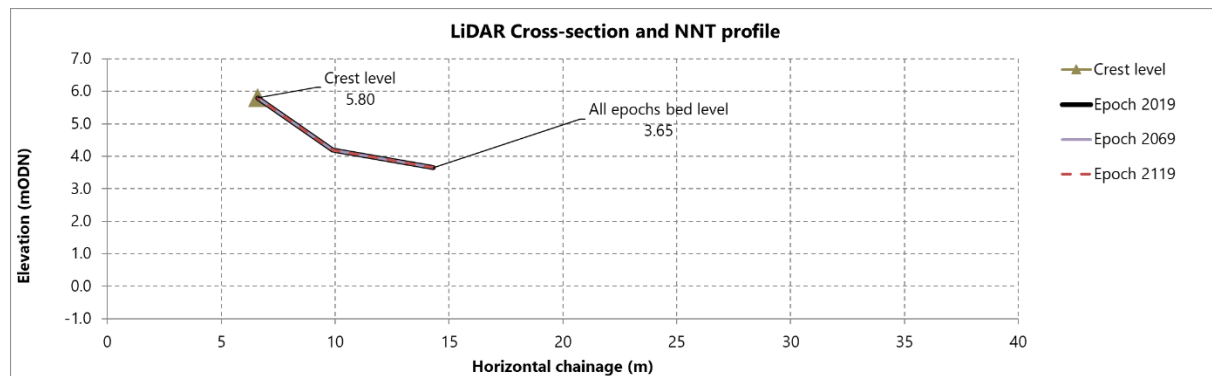


Figure 38. Profile 60: Base Case

Consideration was also given to the area of large dunes at Profile 30, shown in Figure 26. These dunes provide protection to the Barmouth Frontage and hence wave overtopping is not expected at this location. Still water levels are predicted to be higher than the dune crest which stands at 4.7 mODN for events greater than and equal to a 0.33 % AEP in epoch 2069 and events greater than and equal to 50 % in epoch 2119. Despite this the water depths at the structure are likely to be very small and therefore waves are expected to break at the location of the submerged dunes before reaching the frontage.

## 5.3 Base case overtopping results

### 5.3.1 Introduction

As described in Section 5.2, overtopping rates for Profile 1 have been calculated for each of the wave and water level conditions in the Monte Carlo dataset for all three epochs 2019, 2069 and 2119. From the resulting datasets, a count back approach has been applied to obtain overtopping rates for the following AEPs: 100%, 10%, 2%, 1%, 0.5% and 0.1%. The resultant overtopping rates are provided in Table 8 below.

The overtopping rates for Profile 7, 10 and 60 are provided in Table 9, Table 10 and Table 11, respectively. These have used The Pairings to derive Associated Overtopping as discussed in Section 5.1.3 and should be considered indicative for OBC purposes.

### 5.3.2 Results

Table 8. Profile 1 Base Case: Overtopping rates for Barmouth North Promenade Northern Section

| Return Period | AEP (%) | Overtopping Rate (l/s/m) |            |            |
|---------------|---------|--------------------------|------------|------------|
|               |         | Epoch 2019               | Epoch 2069 | Epoch 2119 |
| 1:1           | 100     | 29                       | 38         | 121        |
| 1:10          | 10      | 88                       | 124        | null       |
| 1:50          | 2       | 126                      | 180        | null       |
| 1:100         | 1       | 145                      | 207        | null       |
| 1:200         | 0.5     | 163                      | 246        | null       |
| 1:1000        | 0.1     | 219                      | null       | null       |

**Table 9. Profile 7 Base Case: Associated Overtopping rates for Barmouth North Promenade Southern Section**

| Return Period                                              | AEP (%) | Associated Overtopping Rate (l/s/m) |                               |                               |
|------------------------------------------------------------|---------|-------------------------------------|-------------------------------|-------------------------------|
| Event from Northern Section of North Promenade (Profile 1) |         | Epoch 2019                          | Epoch 2069                    | Epoch 2119                    |
| 1:1                                                        | 100     | 10                                  | 16                            | 49                            |
| 1:10                                                       | 10      | 22                                  | 38                            | no associated event available |
| 1:50                                                       | 2       | 31                                  | 66                            | no associated event available |
| 1:100                                                      | 1       | 48                                  | 72                            | no associated event available |
| 1:200                                                      | 0.5     | 46                                  | 101                           | no associated event available |
| 1:1000                                                     | 0.1     | 59                                  | no associated event available | no associated event available |

**Table 10. Profile 10 Base Case: Associated Overtopping rates for shingle ridge**

| Return Period                                              | AEP (%) | Associated Overtopping Rate (l/s/m) |                               |                               |
|------------------------------------------------------------|---------|-------------------------------------|-------------------------------|-------------------------------|
| Event from Northern Section of North Promenade (Profile 1) |         | Epoch 2019                          | Epoch 2069                    | Epoch 2119                    |
| 1:1                                                        | 100     | 6                                   | 9                             | 17                            |
| 1:10                                                       | 10      | 12                                  | 16                            | no associated event available |
| 1:50                                                       | 2       | 14                                  | 27                            | no associated event available |
| 1:100                                                      | 1       | 27                                  | 33                            | no associated event available |
| 1:200                                                      | 0.5     | 24                                  | 56                            | no associated event available |
| 1:1000                                                     | 0.1     | 26                                  | no associated event available | no associated event available |

**Table 11. Profile 60 Base Case: Associated Overtopping rates for Barmouth South**

| Return Period                                              | AEP (%) | Associated Overtopping Rate (l/s/m) |                               |                               |
|------------------------------------------------------------|---------|-------------------------------------|-------------------------------|-------------------------------|
| Event from Northern Section of North Promenade (Profile 1) |         | Epoch 2019                          | Epoch 2069                    | Epoch 2119                    |
| 1:1                                                        | 100     | null                                | null                          | <0.1                          |
| 1:10                                                       | 10      | null                                | null                          | no associated event available |
| 1:50                                                       | 2       | < 0.1                               | < 1                           | no associated event available |
| 1:100                                                      | 1       | < 0.1                               | <1                            | no associated event available |
| 1:200                                                      | 0.5     | < 1                                 | null                          | no associated event available |
| 1:1000                                                     | 0.1     | < 1                                 | no associated event available | no associated event available |

### 5.3.3 Discussion

Of the four profiles examined, the overtopping rate is predicted to be highest at the northern section of North Promenade (Profile 1). The present-day overtopping rate predicted at Profile 1, is 163 l/s/m for a 0.5% AEP (1:200 year) event.

This rate of overtopping is very significant and based on EurOtop 2007 limits for overtopping for pedestrians (Table 12 and Table 13), both vehicles and pedestrians would need to be stopped from using the promenade.

**Table 12. Limits for overtopping for pedestrians**

| Hazard Type and Reason                                                                                                                                 | Mean Discharge<br>Q (l/s/m) | Max. Volume<br>V <sub>max</sub> (l/m) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|---------------------------------------|
| Trained staff, well shod and protected, expecting to get wet, overtopping flows at lower levels only, no falling jet, low danger of fall from walkway. | 1-10                        | 500<br>at low level                   |
| Aware pedestrian, clear view of sea, not easily upset or frightened, able to tolerate getting wet, wide walkway.                                       | 0.1                         | 20 – 50<br>at high level or velocity  |

Source: EurOtop, 2007

**Table 13. Limits for overtopping for vehicles**

| Hazard Type and Reason                                                                                                                                                                                                                            | Mean Discharge<br>Q (l/s/m) | Max. Volume<br>V <sub>max</sub> (l/m) |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|---------------------------------------|
| Driving at low speed, overtopping by pulsating flows at low depths, no falling jets, vehicle not immersed.                                                                                                                                        | 10 – 50*                    | 100 – 1,000                           |
| Driving at moderate or high speed, impulsive overtopping giving falling or high velocity jets.                                                                                                                                                    | 0.01 – 0.05**               | 5 – 50<br>at high level or velocity   |
| <p>* Overtopping limit is related to the effective overtopping at the highway location.</p> <p>** Overtopping limit is related to the effective overtopping at the defence location with the highway/motorway immediately behind the defence.</p> |                             |                                       |

Source: EurOtop, 2007

EurOtop 2007 identifies that damage is expected to occur to paved or armoured promenade behind a seawall at discharge rates of more than 200 l/s/m (Table 14). It also notes that the 200 l/s/m threshold reduces when crests and rear slopes are not well protected. Such damage was observed during the January 2014 event, when the secondary defence wall at Barmouth North Promenade was severely damaged (Figure 39).

**Table 14. Limits for overtopping for property and damage to the defences**

| Hazard Type and Reason                                                                                                                                                         | Mean Discharge<br>Q (l/s/m) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Damage to building structural elements.                                                                                                                                        | 1*                          |
| Damage to equipment set back 5 – 10 m.                                                                                                                                         | 0.4**                       |
| No damage to embankment/seawall if crest and rear slope are well protected.                                                                                                    | 50 – 200                    |
| No damage to embankment/seawall crest and rear face of grass covered embankment of clay.                                                                                       | 1 – 10                      |
| Damage to paved or armoured promenade behind a seawall.                                                                                                                        | 200                         |
| Damage to grassed or lightly protected promenade.                                                                                                                              | 50                          |
| * Overtopping limit is related to the effective overtopping at the location of the building.<br>** Overtopping limit relates to the overtopping rates at the defence location. |                             |

Source: EurOtop, 2007

Source: <https://naturalresources.wales>**Figure 39. Damage to Barmouth North Promenade following January 2014 Day storm**

By comparing the photographic evidence of overtopping at Barmouth North Promenade during various storm events, with the overtopping threshold limits in the EurOtop 2007 manual, the predicted overtopping rates appear reasonable.

For future epochs, overtopping rates at Profile 1 are predicted to increase significantly. For example, a 0.5 % AEP event in epoch 2069 is predicted to have overtopping rates over 50 % higher than the same event in epoch 2019 (246 l/s/m compared with 163 l/s/m). Furthermore, it is noted that a 100 % AEP event in epoch 2119 is predicted to have a similar overtopping rate (121 l/s/m) as a 2 % AEP event (126 l/s/m) in epoch 2019. For epoch 2119, overtopping rates above the 100 % AEP cannot be reported as the extent of overtopping expected is greater than that tested in the physical tests that inform the EurOtop NNT.

Overtopping rates at Profile 10, to the north of the promenade are predicted to be lower than those at the promenade due to the protection afforded by the shingle ridge but rates are still significant.

At Profile 60 (Barmouth South) very low overtopping rates are predicted due to the high beach level at the toe of the structure. Video footage from the January 2014 storm shows evidence of the beach and dunes protecting Barmouth South from overtopping (Figure 40).

These results, show that the overtopping rates predicted for the base case are consistent with events that are known to have occurred in the recent past. This helps to provide valuable evidence that the approach and the results of the modelling and overtopping assessments are appropriate to examined future scenarios and support the development of the OBC.



Image from a video: <https://www.youtube.com/watch?v=78lo4DW2VjU&feature=youtu.be>

**Figure 40.** Beach and dunes at Barmouth South giving protection from overtopping during January 2014 storm

## 5.4 Do nothing overtopping results

### 5.4.1 Results

This scenario has been completed for Profile 1 and assumes failure of the primary wall as described in section 5.2. The resultant overtopping rates are provided in Table 15.

**Table 15.** Profile 1: Do Nothing Overtopping

| Return Period | AEP (%) | Overtopping Rate (l/s/m) |            |            |
|---------------|---------|--------------------------|------------|------------|
|               |         | Epoch 2019               | Epoch 2069 | Epoch 2119 |
| 1:1           | 100     | 189                      | 200        | null       |
| 1:10          | 10      | 333                      | null       | null       |
| 1:50          | 2       | null                     | null       | null       |
| 1:100         | 1       | null                     | null       | null       |
| 1:200         | 0.5     | null                     | null       | null       |
| 1:1000        | 0.1     | null                     | null       | null       |

## 5.4.2 Discussion

The overtopping results shown in Table 15 illustrate the importance of the primary wall. Without the primary wall in place significant overtopping would be expected across all epochs with still water level overtopping expected to occur for AEPs less than 5% for epoch 2119 (ABPmer, 2019).

## 5.4.3 Do something overtopping results

### 5.4.4 Introduction

The representation of the Do Something Scenario for Profile 1 is provided in section 5.2 and completed for representative crest heights of 6 m, 6.25 m and 7 m (using the Monte Carlo analysis). The resultant overtopping rates are provided in Table 16 below for all three epochs.

For Profile 7, a new set of 11 'Do Something Pairings' have been derived for each AEP based upon the Monte Carlo count-back as described in Section 5.1.3 to provide Associated Overtopping. As shown in Table 16, the 7 m crest level for Profile 1 provides a complete dataset for deriving the associated Profile 7 Pairings. The 7 m Monte Carlo dataset has therefore been used to derive the Profile 7 Do Something Pairings and the Associated Overtopping is provided in Table 17. As discussed in section 5.1.1, these data should be used for OBC optioneering only.

### 5.4.5 Results

Table 16. Profile 1: Do Something Overtopping

| Return Period      | AEP (%) | Overtopping Rate (l/s/m) |            |            |
|--------------------|---------|--------------------------|------------|------------|
|                    |         | Epoch 2019               | Epoch 2069 | Epoch 2119 |
| Crest Level 6 m    |         |                          |            |            |
| 1:1                | 100     | 9                        | 12         | 92         |
| 1:10               | 10      | 53                       | 97         | 296        |
| 1:50               | 2       | 95                       | 160        | null       |
| 1:100              | 1       | 117                      | 196        | null       |
| 1:200              | 0.5     | 138                      | 234        | null       |
| 1:1000             | 0.1     | 206                      | null       | null       |
| Crest Level 6.25 m |         |                          |            |            |
| 1:1                | 100     | 6                        | 8          | 62         |
| 1:10               | 10      | 22                       | 66         | 216        |
| 1:50               | 2       | 65                       | 118        | null       |
| 1:100              | 1       | 82                       | 145        | null       |
| 1:200              | 0.5     | 98                       | 175        | null       |
| 1:1000             | 0.1     | 149                      | 247        | null       |
| Crest Level 7 m    |         |                          |            |            |
| 1:1                | 100     | 1                        | 2          | 11         |
| 1:10               | 10      | 6                        | 14         | 79         |
| 1:50               | 2       | 13                       | 31         | 135        |
| 1:100              | 1       | 17                       | 41         | 156        |
| 1:200              | 0.5     | 21                       | 49         | 180        |
| 1:1000             | 0.1     | 50                       | 71         | 259        |

Table 17. Profile 7: Do Something Associated Overtopping

| Return Period                                              | AEP (%) | Associated Overtopping Rate (l/s/m) |            |            |
|------------------------------------------------------------|---------|-------------------------------------|------------|------------|
| Event from Northern Section of North Promenade (Profile 1) |         | Epoch 2019                          | Epoch 2069 | Epoch 2119 |
| <b>Crest Level 6 m</b>                                     |         |                                     |            |            |
| 1:1                                                        | 100     | 5                                   | 7          | 9          |
| 1:10                                                       | 10      | 15                                  | 23         | 28         |
| 1:50                                                       | 2       | 29                                  | 38         | 49         |
| 1:100                                                      | 1       | 33                                  | 47         | 77         |
| 1:200                                                      | 0.5     | 34                                  | 49         | 106        |
| 1:1000                                                     | 0.1     | 52                                  | 67         | null       |

### 5.4.6 Discussion

For the 'Do Something' at Profile 1, an overtopping rate of < 200 l/s/m is achieved for all AEP's up to and including the 0.5%, across all epochs with a 7 m crest height. With a crest height of 6.25 m, overtopping rates of < 200 l/s/m would be met for AEP up to and including the 0.5% AEP, for epoch 2019 and 2069. However, significant overtopping would exceed this criteria in epoch 2119 for a 10% AEP event (216 l/s/m for a 10% AEP event).

The 'Do Something' Profile 7, with a 6 m crest height, is predicted to result in overtopping rates of <200 l/s/m, for the 0.5% AEP event across all epochs.

## 6 Design Hydrographs

### 6.1 Methodology

To estimate overtopping volumes during a storm event, overtopping hydrographs have been generated. For each epoch and defence schematisation, an overtopping hydrograph has been created for the 0.5% AEP (1:200 year) event. Where the 0.5% AEP event is not available, the smallest available AEP was used to create the hydrograph. This hydrograph has then been scaled to produce hydrographs for the remaining AEPs: 100%, 10%, 2%, 1% and 0.1%.

To generate the overtopping hydrographs, it was first necessary to develop **design tide hydrographs**. This was achieved using the Environment Agency preferred method (Environment Agency, 2011). The design tide hydrograph was constructed using a mean high-water spring (MHWS) base astronomical tide for Barmouth, which was generated using Total Tide. This base astronomical tide was combined with a scaled Barmouth design surge shape profile (Environment Agency, 2011) such that the water level at the peak of the overtopping event is equivalent to the required water level for the overtopping event.

To create **design overtopping hydrographs** the design tidal hydrograph was run through the NNT for each profile. This provided an overtopping profile shape unique to each defence for each epoch and each scenario.

In this assessment, a uniform wave condition was used over the design tide hydrograph. This wave condition used was taken from one of the Monte Carlo events that produced a 0.5 % overtopping AEP at Profile 1. The 0.5 % AEP hydrograph was then scaled for the remaining AEPs: 100%, 10%, 2%, 1% and 0.1%

### 6.2 Results

The resultant overtopping hydrographs are presented in Figure 41 to Figure 44 have been provided in digital format to be used in TUFLOW model inputs.

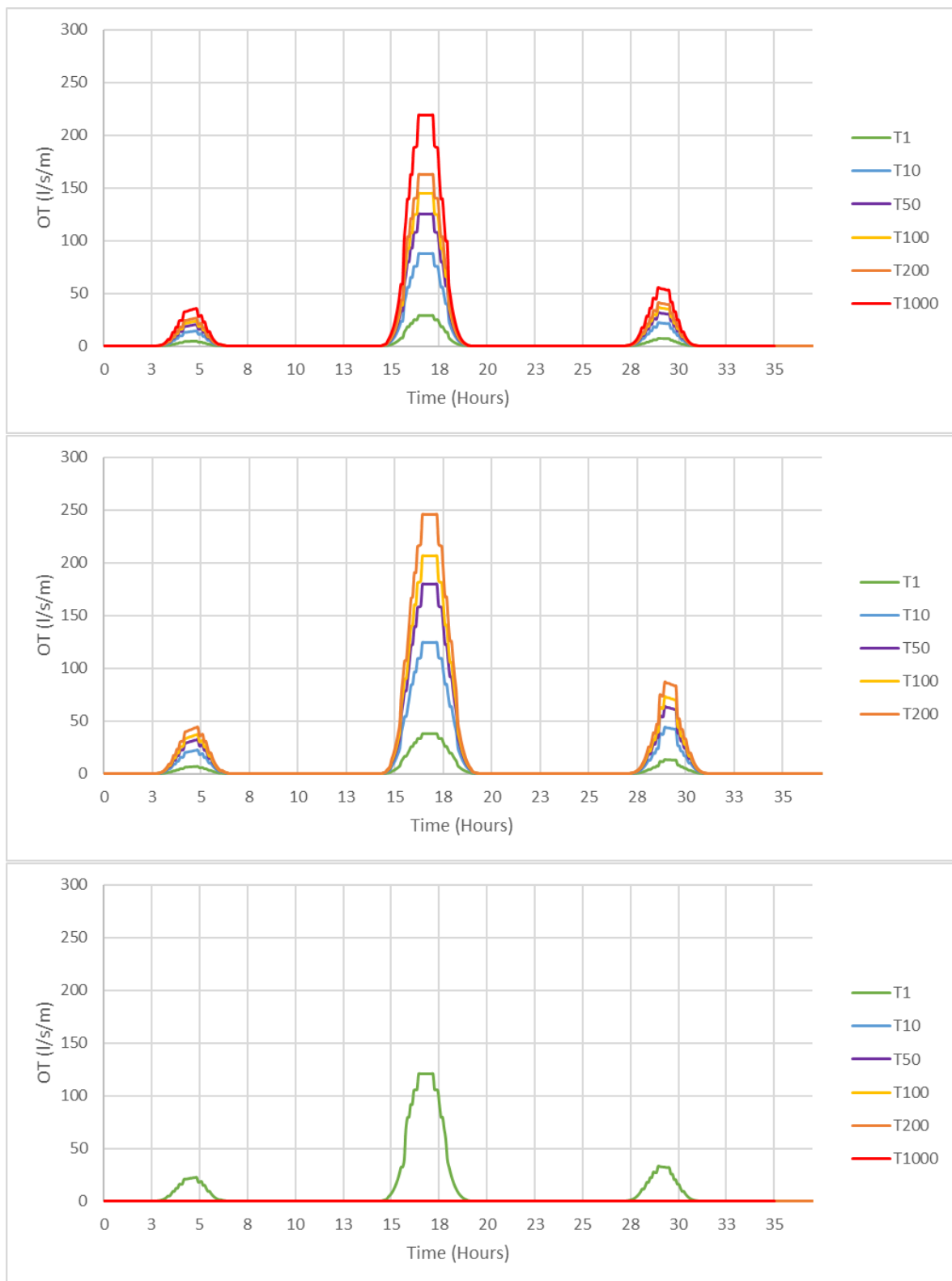


Figure 41. Profile 1 Baseline hydrographs: epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower)<sup>4</sup>

<sup>4</sup> No hydrographs are presented where null values occur even though overtopping would be expected

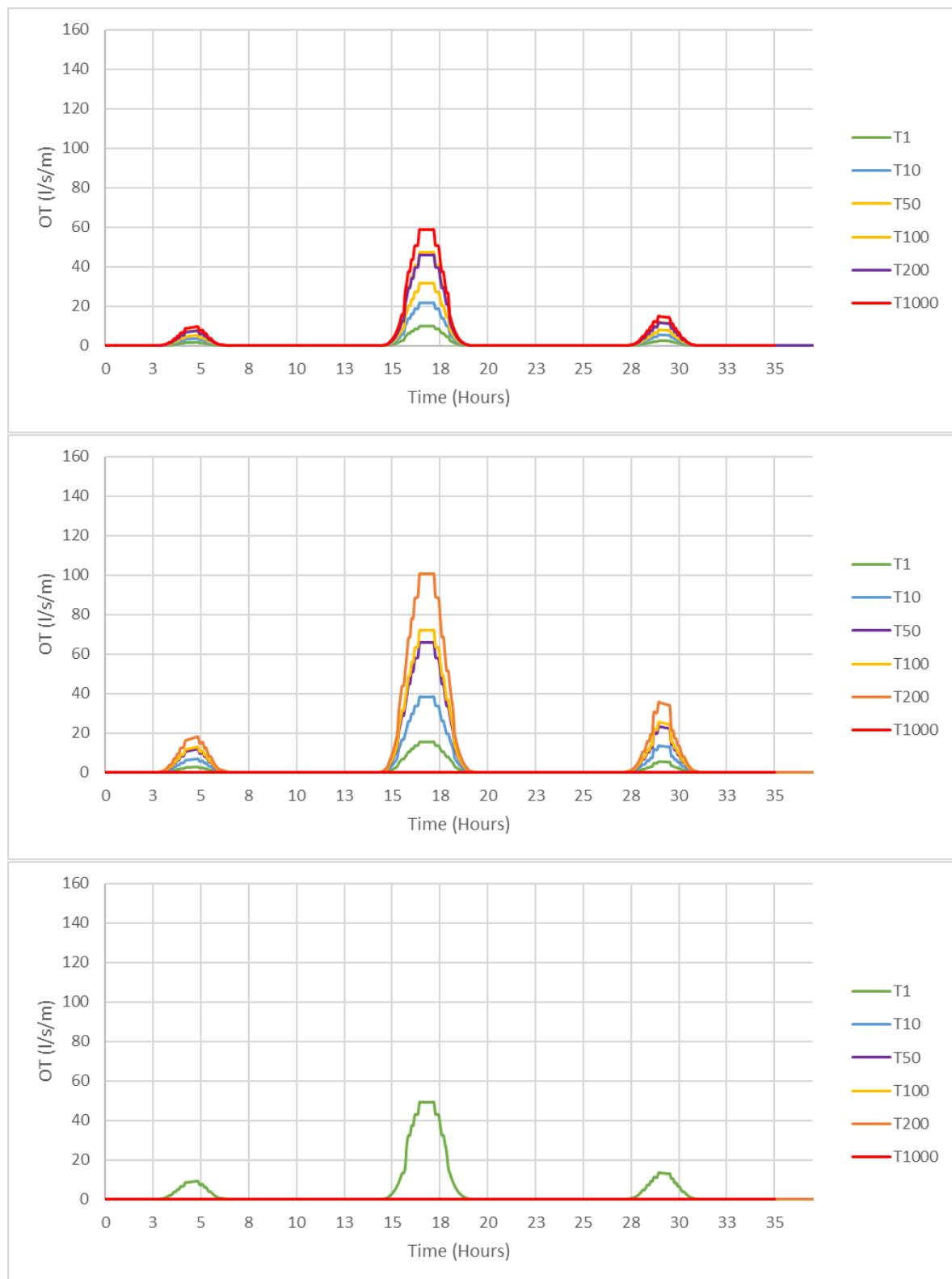
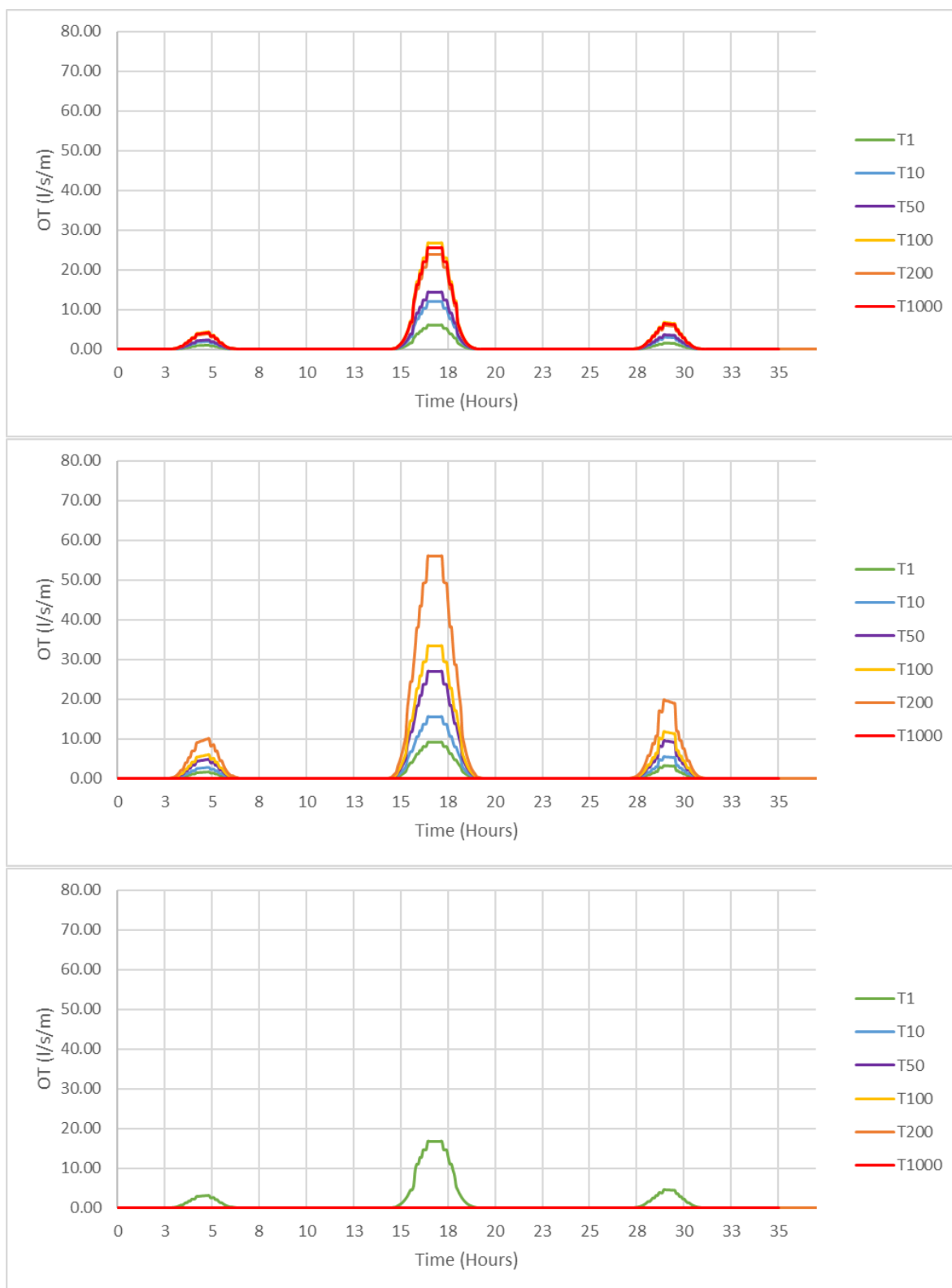


Figure 42. Profile 7 Baseline hydrograph: epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower) <sup>5</sup>

<sup>5</sup> No hydrographs are presented where null values occur even though overtopping would be expected



**Figure 43.** Profile 10 Baseline hydrographs: epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower) <sup>6</sup>

<sup>6</sup> No hydrographs are presented where null values occur even though overtopping would be expected

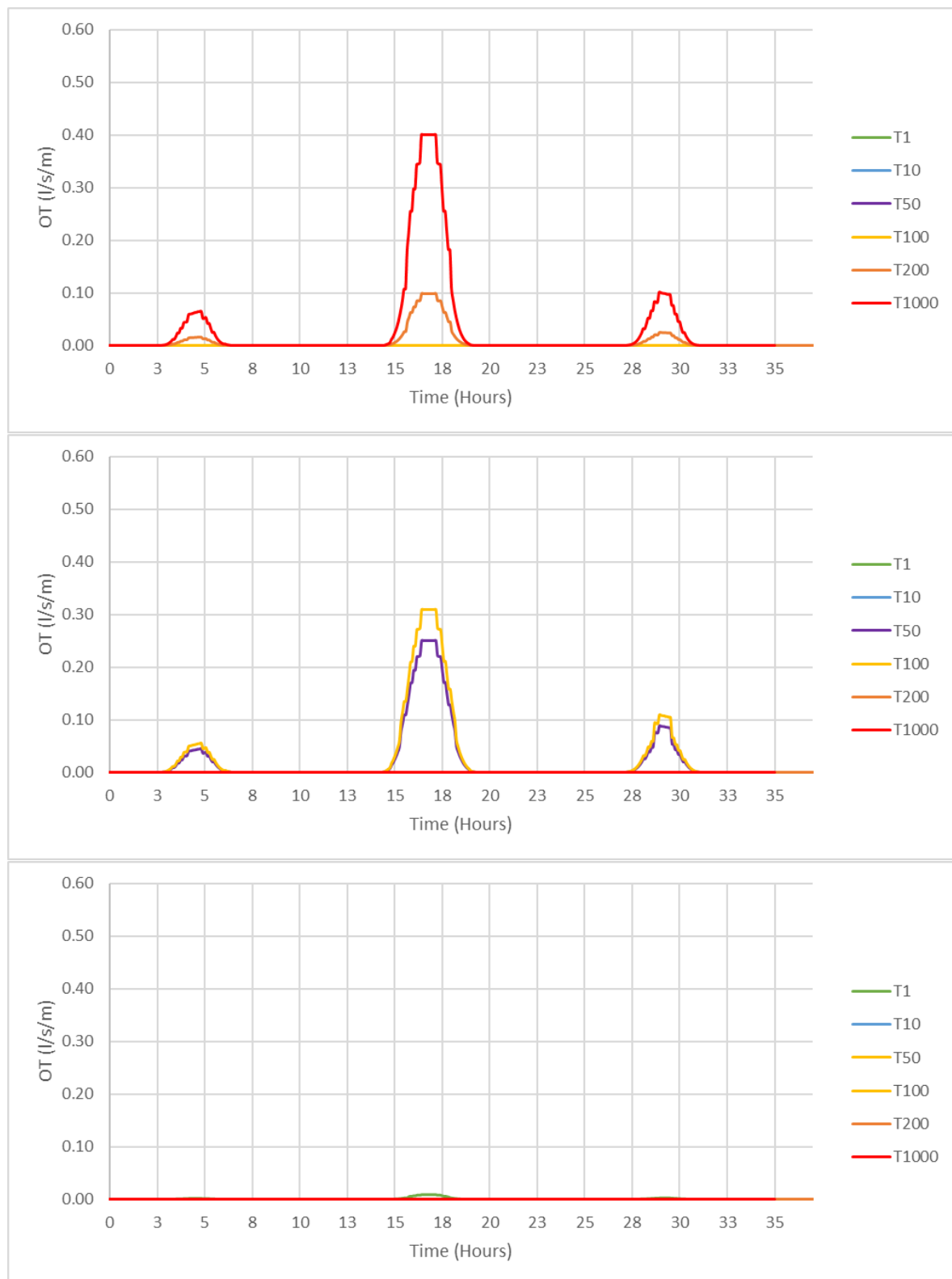


Figure 44. Profile 60 Baseline hydrographs: epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower) <sup>7</sup>

<sup>7</sup> No hydrographs are presented where null values occur even though overtopping would be expected

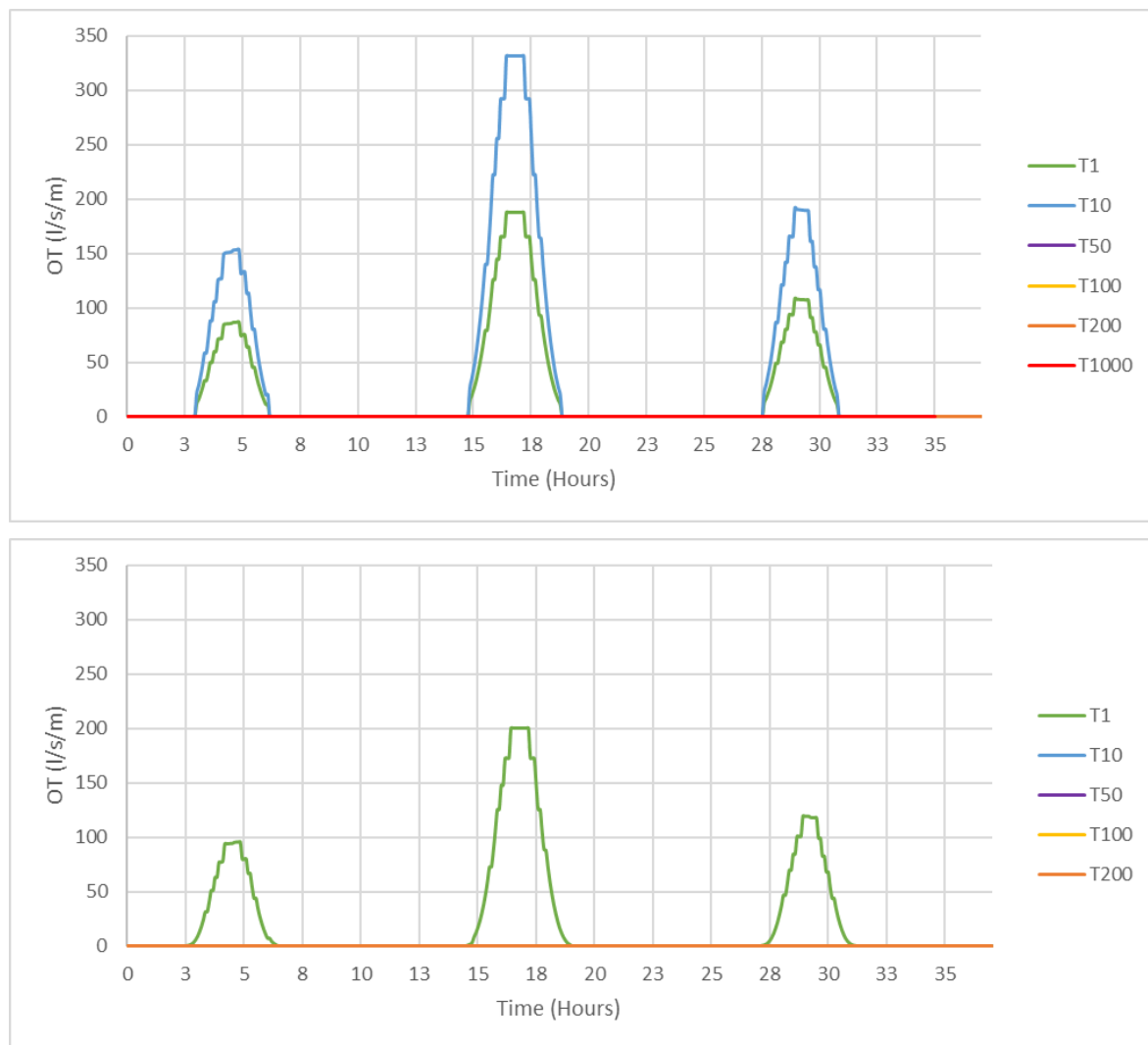


Figure 45. Profile 1: Do Nothing hydrographs: epoch 2019 (upper) and epoch 2069 (middle).<sup>8</sup>

<sup>8</sup> No hydrographs are presented where null values occur even though overtopping would be expected

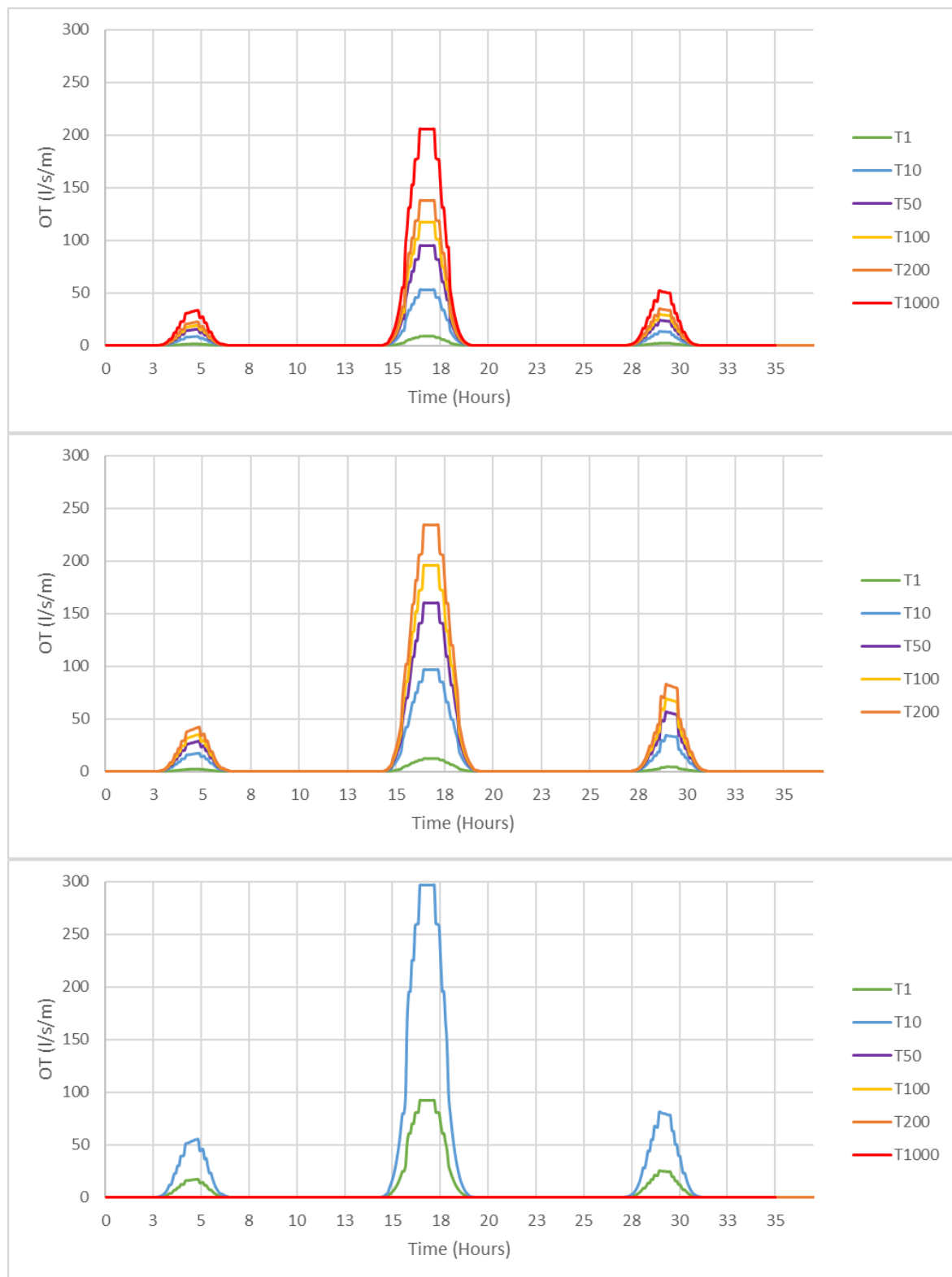


Figure 46. Profile 1: Do Something hydrographs (6 m Crest Level): epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower)

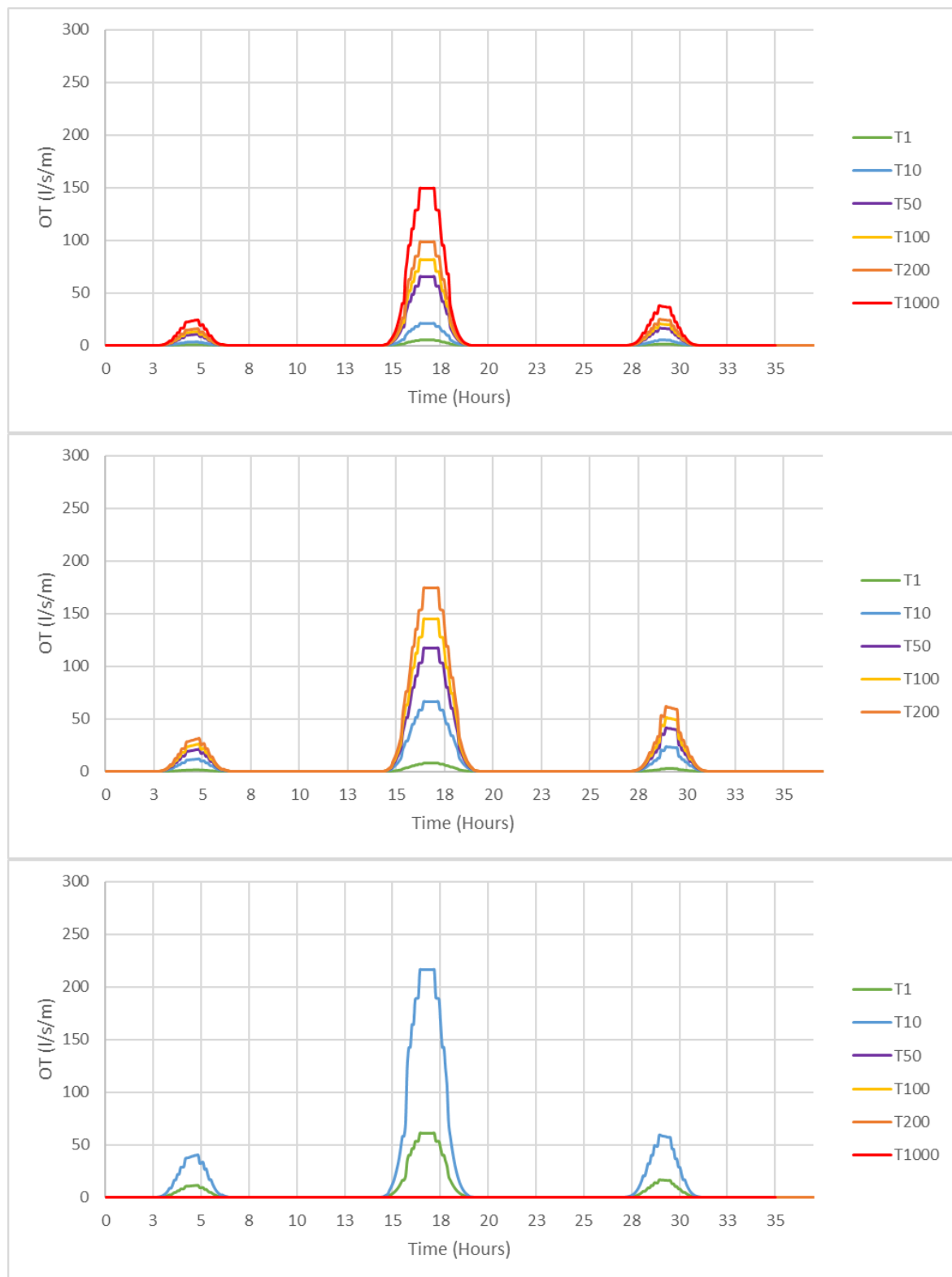


Figure 47. Profile 1: Do Something hydrographs (6.25 m Crest Level): epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower)<sup>9</sup>

<sup>9</sup> No hydrographs are presented where null values occur even though overtopping would be expected

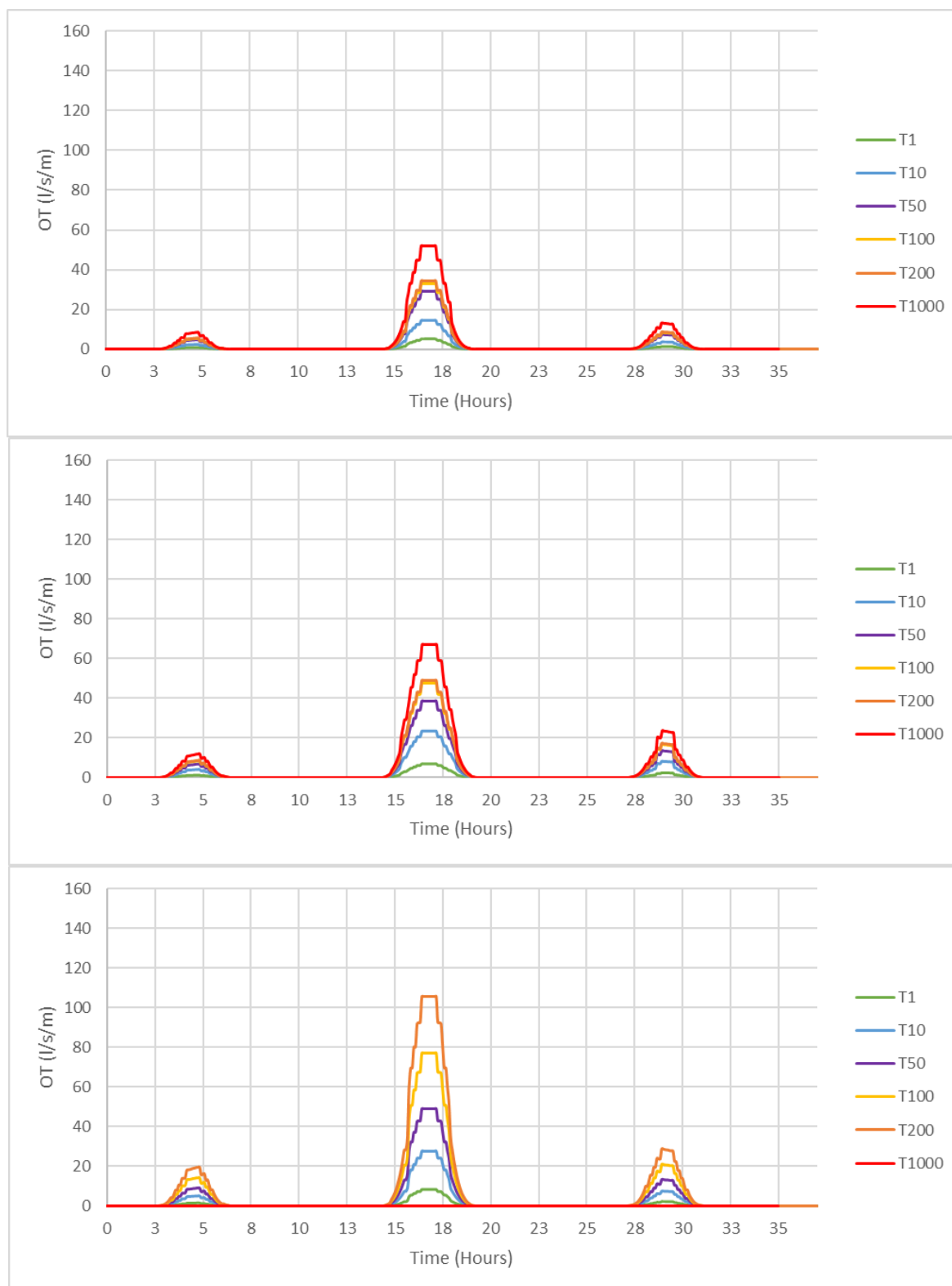


Figure 48. Profile 1: Do Something hydrographs (7 m Crest Level): epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower)<sup>10</sup>

<sup>10</sup> No hydrographs are presented where null values occur even though overtopping would be expected

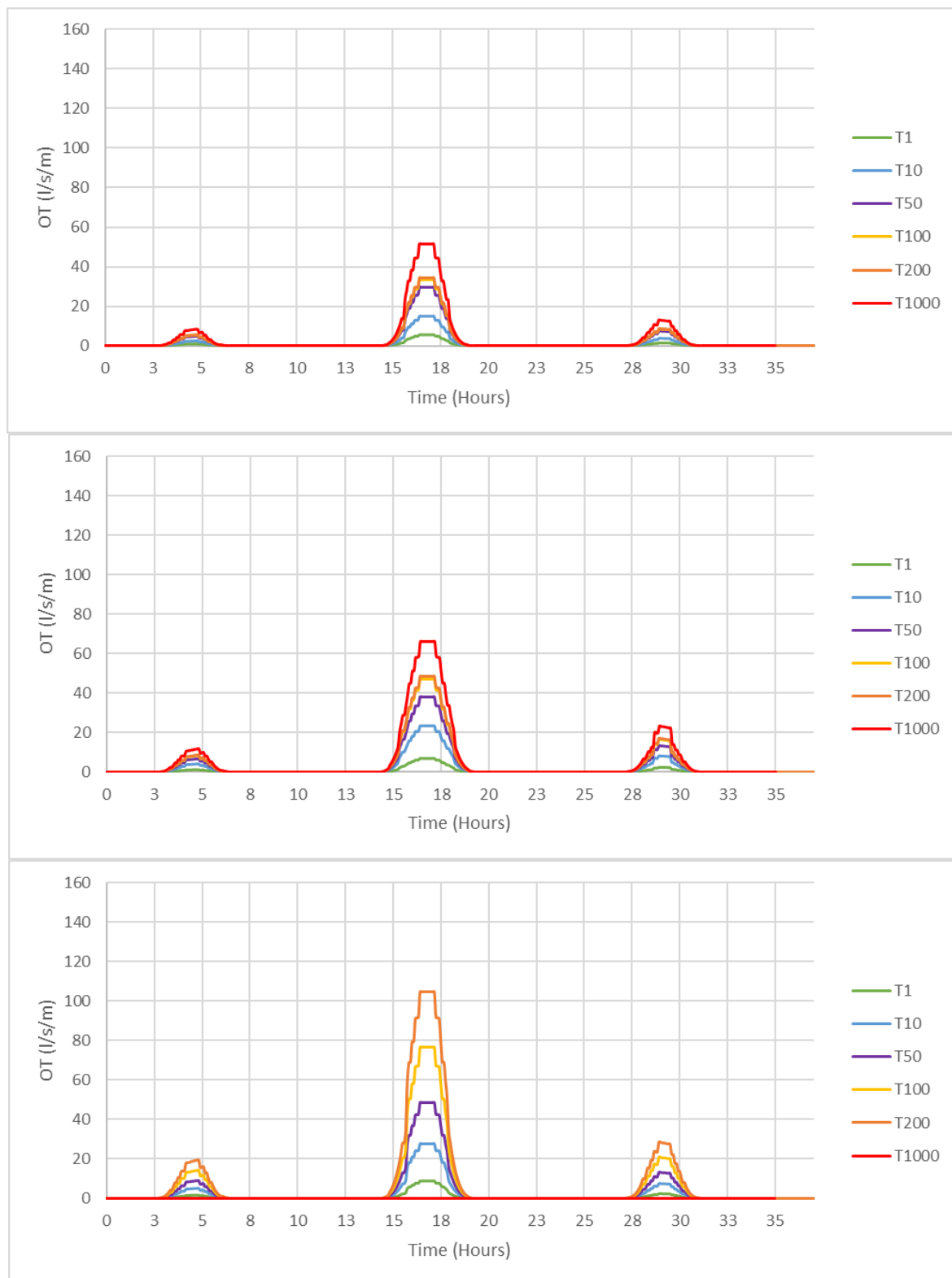


Figure 49. Profile 7: Do Something hydrographs (6 m Crest Level): epoch 2019 (upper), epoch 2069 (middle) and epoch 2119 (lower) <sup>11</sup>

<sup>11</sup> No hydrographs are presented where null values occur even though overtopping would be expected

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## 8 Abbreviations/Acronyms

|          |                                                                                                                                                      |
|----------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1D       | One Dimension(al)                                                                                                                                    |
| Ac       | Armour Height                                                                                                                                        |
| AEP      | Annual Exceedance Probability                                                                                                                        |
| B        | Berm Width                                                                                                                                           |
| BAP      | Biodiversity Action Plan                                                                                                                             |
| CFBD     | Coastal Flood Boundary Dataset                                                                                                                       |
| CFSR     | Climate Forecast System Reanalysis                                                                                                                   |
| CFSv2    | Climate Forecast System v2                                                                                                                           |
| CGC      | Cyngor Gwynedd Council                                                                                                                               |
| CLASH    | Crest Level Assessment of Coastal Structures by Full-Scale Monitoring, Neural Network Prediction and Hazard Analysis on Permissible Wave Overtopping |
| d.p.     | Decimal Place                                                                                                                                        |
| DCL      | Defence Crest Level                                                                                                                                  |
| DHI      | Danish Hydraulic Institute                                                                                                                           |
| DSM      | Digital Surface Model                                                                                                                                |
| EMODnet  | The European Marine Observation and Data Network                                                                                                     |
| EVA      | Extreme Value Analysis                                                                                                                               |
| FM       | Flexible Mesh                                                                                                                                        |
| Gc       | Crest Width                                                                                                                                          |
| GPD      | Generalised Pareto Distribution                                                                                                                      |
| hb       | Water Depth of Berm                                                                                                                                  |
| Hs       | Significant Wave Height                                                                                                                              |
| JOINSEA  | Joint Probability of Waves and Water Levels software                                                                                                 |
| JPA      | Joint Probability Analysis                                                                                                                           |
| LiDAR    | Light Detection and Ranging                                                                                                                          |
| Litdrift | Software programme simulating non-cohesive sediment transport (DHI)                                                                                  |
| MHWS     | Mean High-Water Spring                                                                                                                               |
| MRSL     | Mean Relative Sea Level                                                                                                                              |
| MRSLR    | Mean Relative Sea Level Rise                                                                                                                         |
| NAI      | No Active Intervention                                                                                                                               |
| NCAR     | National Center for Atmospheric Research                                                                                                             |
| NCEP     | National Centers for Environmental Prediction                                                                                                        |
| NN       | Neural Network                                                                                                                                       |
| NNT      | Neural Network Tool                                                                                                                                  |
| OBC      | Outline Business Case                                                                                                                                |
| ODN      | Ordnance Datum Newlyn                                                                                                                                |
| Rc       | Crest Freeboard                                                                                                                                      |
| SAC      | Special Area of Conservation                                                                                                                         |
| SMP      | Shoreline Management Plan                                                                                                                            |
| SSSI     | Site of Special Scientific Interest                                                                                                                  |
| SW       | Spectral Wave                                                                                                                                        |
| SWL      | Still Water Level                                                                                                                                    |
| Tm-1,0   | Mean Energy Wave Period                                                                                                                              |
| UAV      | Unmanned Aerial Vehicle                                                                                                                              |
| UK       | United Kingdom                                                                                                                                       |
| UKCP09   | UK Climate Predictions (2009)                                                                                                                        |
| UKHO     | United Kingdom Hydrographic Office                                                                                                                   |
| WL       | Water Level                                                                                                                                          |

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|     |                                          |
|-----|------------------------------------------|
| YGC | Ymgynghoriaeth Gwynedd Consultancy (YGC) |
| αd  | Lower Slope                              |
| αu  | Upper Slope                              |
| γf  | Roughness                                |

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

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