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Local delivery of global value

Additional support for extreme sea level characterisation at Sizewell C

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6th July 2022

PROTECT-PROPRIETARY

EDF R&D UK Centre Limited.

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Short Summary

EDF R&D UK Centre supports Nuclear New Build in assessments regarding the permanent sea defences for Sizewell C (SZC). This report provides support for extreme sea level characterisation at SZC that supersedes and extends the 2020 EDF R&D UK Centre extreme sea level analysis [1] by:

- Updating the extreme value analysis of sea level for the present climate by combining new observations of skew surges and tides at Lowestoft between 2020-2022.
- Applying methods that include historical events of extreme high sea level between 1900-1964 (start of tide gauge observations at Lowestoft) into the estimation of extreme sea levels for the present climate.
- Assessing similarities and differences of the 2018 Environment Agency (EA) Coastal Boundaries Model [2] and the current analysis, by comparing results of 10-year to 10,000-year return periods of sea level for various confidence intervals.
- [redacted]

Keywords

Sizewell C, extreme value analysis, skew surge joint probability method, skew surge, tides, sea level, Lowestoft, historical data.

Version Control

Version	Date	Author	Description
1.0	21/04/2022	[redacted]	Technical report with client comments addressed
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Executive summary

EDF R&D UK Centre (UKC) supports Nuclear New Build in assessments regarding the design of the permanent sea defences for Sizewell C (SZC) which include hard and soft coastal defence features to ensure nuclear safety against coastal flooding. In 2020, EDF R&D UKC used extreme value modelling of tide gauge data to estimate extreme sea levels at the SZC site [1]. The report is superseded by the current report which extends the 2020 report by:

- Updating the extreme value analysis of sea level for the present climate by including new observations of skew surges and tides from the Lowestoft tide gauge (combining observations from 1st of January 2020 to the 31st of January 2022 to the 1964-2019 data available).
- Applying methods to include four historical events of extreme high sea level prior to 1964 (start of tide gauge observations at Lowestoft) into the estimation of extreme sea levels for the present climate.
- Assessing the similarities and differences of the 2018 Environment Agency's (EA) Coastal Boundaries model [2] and the current analysis by comparing results of 10-year to 10,000-year return periods of sea level for various confidence intervals.
- [redacted]

For this work, the following data are used:

- Skew surge and tide observations from the Lowestoft tide gauge from 1st of January 1964 to the 31st of January 2022.
- Four historical events of skew surge and tide between 1900-1964 at Lowestoft.
- [redacted]

The main results of each section are:

- **Update to return levels for Lowestoft tide gauge 1964-2022:** Including an additional 2 years (2020-2022) of tide gauge data in the EVA model leads to very similar but slightly lower return levels because the highest sea levels in the additiona years were relatively low compared to the 1964-2019 data. We refer to the updated model with the additional two years of data as the baseline model.
- **Including historical storms:** Of the models tested, the best model fit was achieved by synthesising new data for the early 1900s using a copy of the observational tide gauge data with the addition of the historical storms. This method provides an increase to the Lowestoft return levels that adds considerable conservatism compared t the baseline model.
- **Comparing EA model outputs with Lowestoft return levels:** The return levels calculated using Lowestoft tide gauge da a closely match those calculated in the EA model. This is as expected since the methodology is the same between the two models and the Lowestoft return levels are derived using an extension of the tide gauge data. Where the Lowestoft tide gauge extrapolations (1964-2022) are slightly lower than the EA model estimates (1964-2018) is because the additional 4 years of data had relatively few extreme high sea level events.
- [redacted]

[redacted]

Contents

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1 Introduction

To support the design of the permanent sea defences for SZC which include hard and soft coastal defence features, EDF R&D UK Centre produced a study in 2020 estimating the extreme sea level return levels at the site in the present climate and at various points in the future [1]. The data was from National Tidal Sea Level Facility's long-running tide gauge at Lowestoft (since 1964) and the Environment Agency's Coastal Boundaries model [2] was used to make an adjustment to the expected sea levels at Sizewell, around 30 km south of Lowestoft.

[redacted] It is noted that the EA Coastal Boundaries model shows a greater reduction from Lowestoft to Sizewell for extreme high water levels at higher return periods whereas the recent high water events analysed by Cefas were not that extreme in magnitude [3]. It is understood that the EA Coastal Boundaries model in the region is not calibrated against any tidal measurement data from coastal locations between Lowestoft and Felixstowe. [redacted]

In considering the extreme high water levels being derived for Sizewell C another important point is the recognition that there were several major storm surge events affecting the southern North Sea in the first half of the 20th century including the well-known event of 1953 [4]. There are fewer events of this magnitude recorded in the tidal gauge data dating back from the present to 1964 at Lowestoft. This could be consistent with there being a multi-decadal storminess cycle which should be accounted for in the prediction of extreme high water levels over the lifetime of Sizewell C.

The above points are addressed in this ext n ion to the work reported in [1]. This work is a high priority for the Sizewell C project as the outputs are needed to inform the selection of the hazard challenge and design basis conditions being used as input to ( ) the multivariate analysis of sea conditions and wave transformations by HR Wallingford, and (ii) the detailed design of the Sizewell C sea defences by Atkins. Extreme high water levels are also relevant to the Sizewell C Pumping Station design which is being adapted from Hinkley Point C.

The report's structure is: Section 2 presents the update of the EVA model of extreme sea levels of [1] using the Skew Surge Joint Probability Method (SSJPM) and more recent observations of skew surges and tides at Lowestoft (1964-2022) alongside historical events. Section 3 compares the EA results with the update provided in Section 2 and highlights the consistency of the results. [redacted] Section 5 concludes the report.

2 Updating Lowestoft extreme sea level estimates and historical storm surge events

This section updates the return levels estimated from Lowestoft tide gauge data using an additional 2 years of data from the previous EDF R&D UKC study [1] and applies several methods to increase the conservatism of the results by adding historical events that occurred before the start of the Lowestoft tide gauge data.

2.1 Data

2.1.1 Lowestoft tide gauge

The available Lowestoft tide gauge data cover the time period between 01/01/1964 and 31/01/2022. This includes an additional 2 years and 1 month (01/01/2020 – 31/01/2022) beyond the data analysed in [1]. Reports [1] and [5] detail more information about the Lowestoft tide gauge which provides sea levels, tides, and skew surges. Skew surge is the differences between highest sea level and highest tide within the same tidal cycle. The application of the EVA requires the data to be stationary, meaning that the statistical distribution of the data does not change through time. Therefore, to analyse the extreme events, the linear trend in the mean sea level and astronomical tide are removed around a control year of 2017 (i.e. 2.27 mm is added to all observations from the year 2016, 4.54 mm is added for 2015 and so on; in the same way 2.27 mm is subtracted for 2018 and so on). The control year is taken as close to the end of the dataset so that it is representative of present-day sea levels. The year 2017 also aligns with the control year used by the EA Coastal Boundaries Model [2] and the previous EDF R&D UKC report [1]. Figure 1 shows the time series of bi-daily skew surges from 1964 to 2022 and Figure 2 shows the histogram of the skew surge where most of the observations are between -/+ 0.5m.

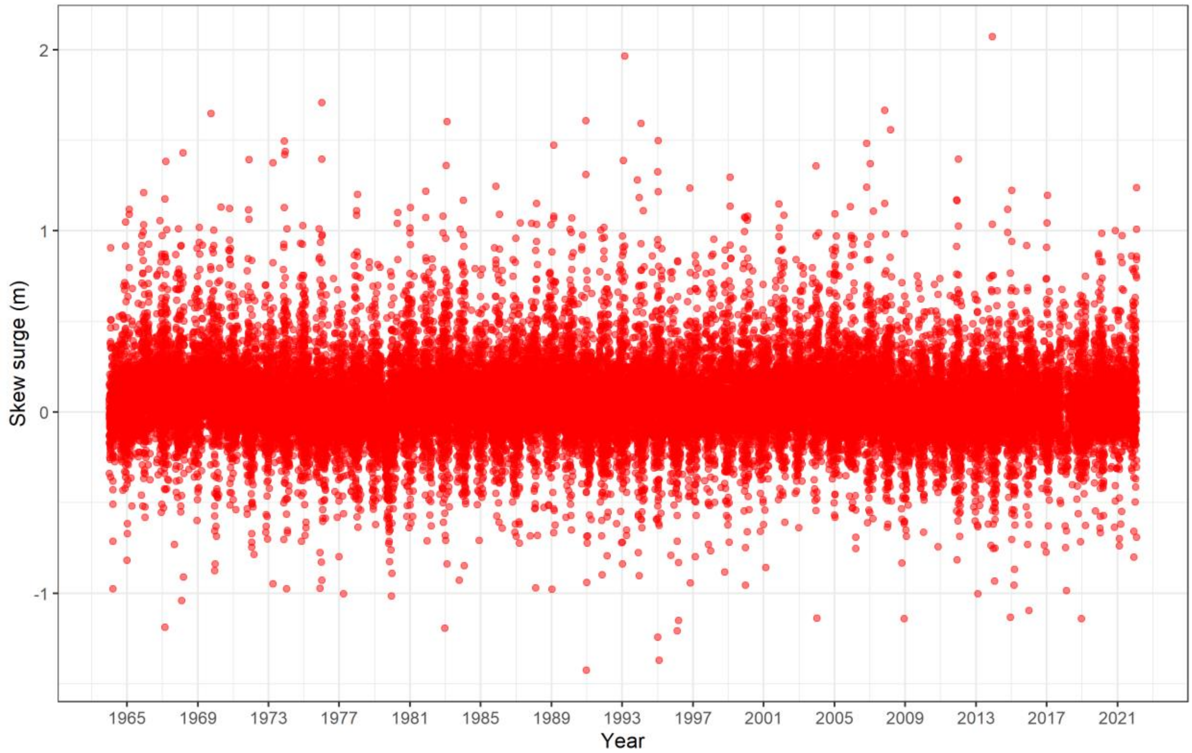

Figure 1: Observations of detrended skew surges at Lowestoft tide gauge from the 1st of January 1964 to the 31st of January 2022. Observations are available at each tidal cycle, approximately twice a day.

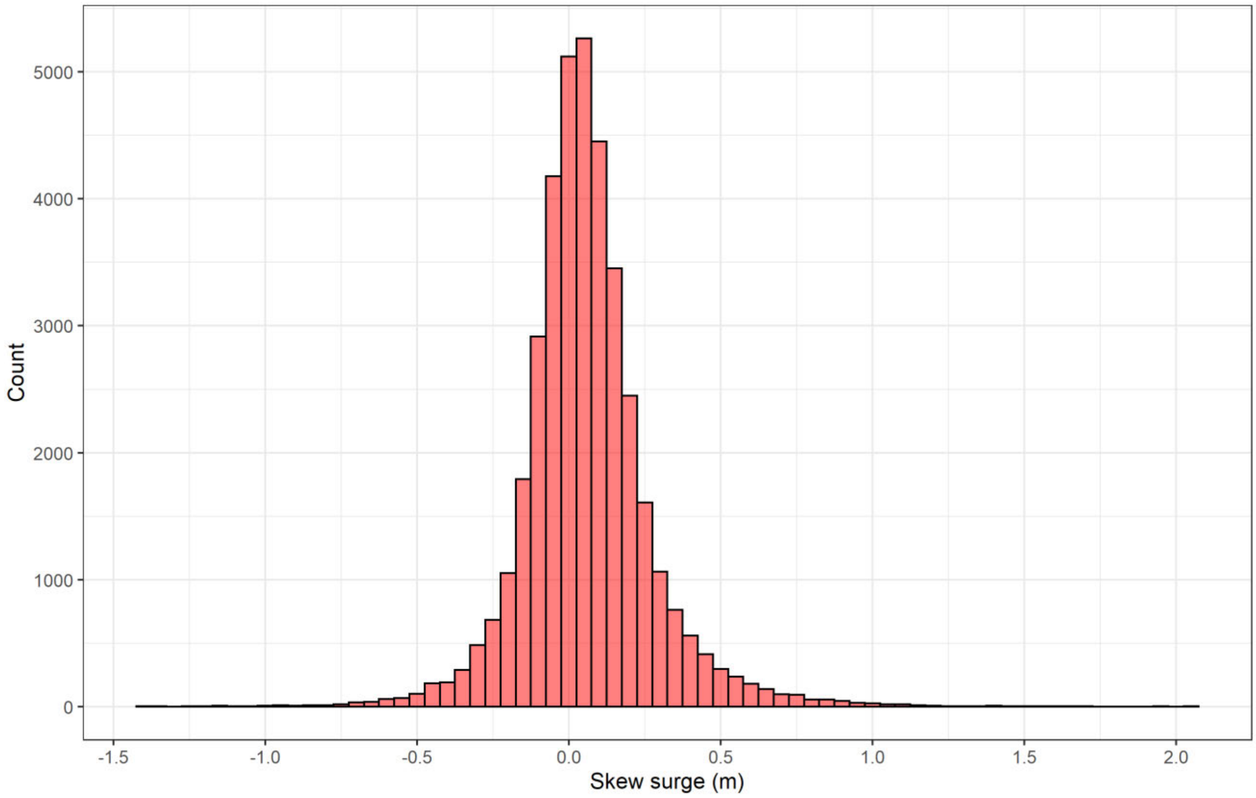

Figure 2: Histogram of twice-daily skew surges at Lowestoft over the period 1964-2022.

To understand the impact of extending the observations time period available, a check of the additional data between 01/01/2020 and 31/01/2022 was performed to see whether there had been any particularly high tides or storm surge events. The data between 01/01/2020 and 31/01/2022 include 73,152 measurements of sea level, 114 (0.16%) missing values, 3,341 (4.57%) values labelled "improbable" by BODC's pre-processing analysis [6], and 9 (0.01%) values that have been interpolated using the surrounding data. When compared to the completeness of the 1964-2019 Lowestoft tide gauge data, analysed in [1], in Table 1, we can see that the availability of the time series over the two periods are very similar, above 95%. For further analysis, Figure 3 illustrates the yearly variation of the proportion of measured (green), interpolated (blue), missing (red) and improbable (orange) sea level data at Lowestoft from 1964 to 2022. The y-axis is zoomed in between 0.74 and 1 which emphasises the lack of data. There are fourteen years with less than 95% of the data available, with the years lacking most of the data being 2016, 2017 and 2018. Nevertheless, the data are overall of high availability and quality and adding the period 2020-2022 to the time period 1964-2019 is beneficial.

Table 2 lists the top 10 highest extreme skew surges at Lowestoft between the 1st of January 2020 and the 31st of January 2022 with associated dates and sea level. The largest skew surge in 2020-2022 occurred during the 2022-01-30 07:30:00 high tide, 1.24m, ranked 32nd highest skew surge out of the whole time series 1964-2022. Maximum skew surge 1964-2022 is 2013-12-05 23:00 at 2.07m. The years 2020-2022 were slightly below average in the frequency and severity of storm surge events. This means that using 2020-2022 year will not challenge the EVA results previously provided in [1].

Table 1: Measured, interpolated, missing and improbable sea level data proportions at Lowestoft between two periods: 1964 to 2019 and 2020-31/01/2022

Value status	1964-2019 [1]	2020 - 31/01/2022 (present report)
Measured	95.79%	95.26%
Missing	1.65%	0.16%
Improbable	2.47%	4.57%
Interpolated	0.09%	0.01%

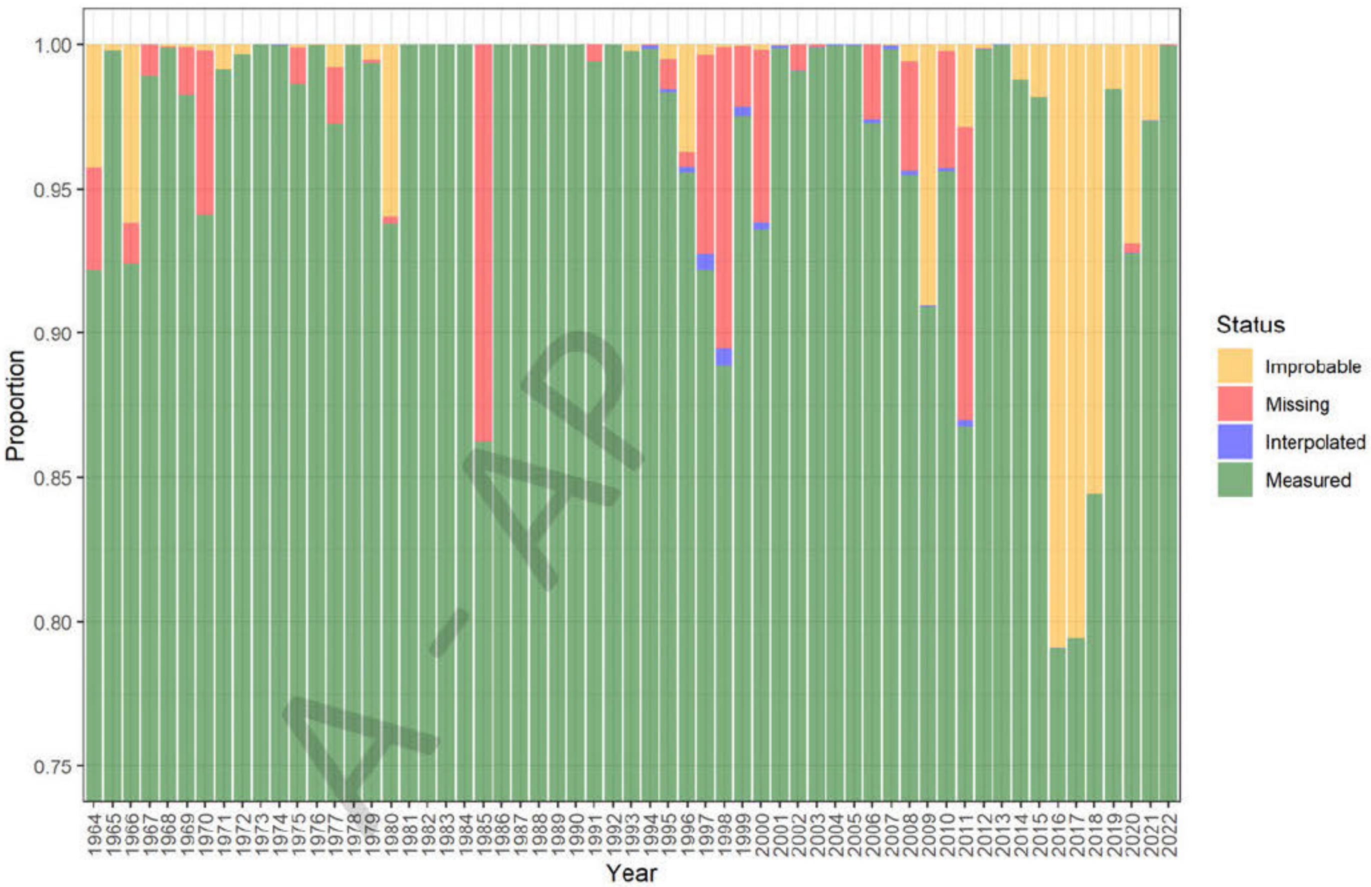

Figure 3: Yearly variation of the proportion of measured (green), interpolated (blue), missing (red) and improbable (orange) sea level data at Lowestoft from 1964 to 2022 (y-axis zoomed in between 0.74 and 1).

Table 2: Top 10 highest extreme skew surges at Lowestoft between the 1st of January 2020 and the 31st of January 2022 with associated dates and sea level (detrending applied). The highest astronomical tide was 1.41mOD and the highest sea level was 2.15mOD

Date and time	Skew surge (m)	Sea level (mOD)	Tide (mOD)
2022-01-30 07:30:00	1.24	2.15	0.91
2022-01-29 19:00:00	1.01	1.79	0.78
2020-11-19 12:15:00	1.00	2.06	1.06
2020-02-10 10:15:00	0.99	2.00	1.01
2021-04-05 15:30:00	0.97	1.58	0.61
2021-10-21 09:30:00	0.86	2.01	1.15
2022-01-31 20:45:00	0.86	1.83	0.98
2021-03-11 20:30:00	0.86	1.73	0.88
2022-01-27 17:00:00	0.84	1.50	0.66
2020-02-20 19:45:00	0.83	1.61	0.78

2.1.2 Historical events between 1900-1964

In extreme value modelling, historical events a e extreme events that occurred before start of the systematic observations (in this case, the Lowestoft tide gauge). The sea level for historical coastal flooding events can be in several ways, including direct measu ements during the event, estimates from the extent of damage caused, and eye-witness accounts. Inc uding historical events in extreme value models often makes them more accurate, especially when extrapola ing to long return periods. If the historical events are more extreme than those in the systematic data, as in this case, then including them in the extreme value model adds to the conservatism of the results.

In this report, we consider historical sea level events around Lowestoft between ~1900 and 1964. In particular, we include four historical events (Table 3) that have been listed in the 2013 BEEMS study into SZC sea levels [5] and were sou ced using Surgewatch [4] and other academic literature [7]. Surgewatch is an interactive database of UK coastal flood events that details 719 storm events from 1014 to 2018 with subjective severity grade from 1 to 6 (lowest to highest severity) based on the magnitude of the event as well as its impact on society. The events included have been verified by researchers at Surgewatch. Alongside these four events, the following three additional historical storms since 1897 were considered but not included due to lack of reliable quantitative data close to the SZC location:

- 28th November 1897[1], severity 5 out of 6: Affected the east coast from Kent in the South of England to Dumfries and Galloway in Scotland. However, no quantitative records exist for the Lowestoft area.

[1] https://www.surgewatch.org/events/1897-11-28/

- 1st November 1921[2], severity 4 out of 6: Affected the south east of England, with reports of the most significant impacts along the Thames estuary. No quantitative records exist for the Lowestoft area.
- 17th December 1921[3], severity 4 out of 6: Affected Scotland and the north of England with particularly severe flooding in Hull. The impacts were less severe in the south of England and no quantitative records exist for the Lowestoft area.

Table 3: Historical data of sea level at Lowestoft, tide and skew surge analysed in the report [5].

Date	Observed sea level, mOD	Tide, mOD	Skew surge, m	SurgeWatch severity grade
6th Jan 1928	3.10	1.1	2.00	5 out of 6
13th Feb 1938	3.25	1.00	2.25	3 out of 6
1st Mar 1949	3.00	0.90	2.10	4 out of 6
31st Jan 1953	3.44	1.00	2.44	6 out of 6

One of the limitations of including historical data into EVA models is that it is extremely difficult to know whether the historical events chosen are the only extreme events in the time period considered. For example, it is possible that there was a storm surge event in the early 1900s that coincided with a low tide, producing an unremarkable sea level that is not recorded. Therefore, most methods require the "perception hypothesis" to be assumed when including historical extremes in EVA models. The perception hypothesis is the assumption that the historical extremes included are the only events that exceed the threshold used to extract extremes between the first historical event and the first recording from the systematic tide gauge data.

The historical data in Table 3 were adjusted for sea level rise with base year of 2017 by linear trend of 2.27mm per year when the SSJPM is applied in Section 2.3.2.

2.2 Methodology

To calculate the return levels for extreme sea levels at Lowestoft we implement SSJPM. This is a best-practice methodology for deriving extreme sea levels used by the EA in their Costal Boundaries modelling in 2011 [8] and 2019 [2] as well as in academic research [9]. The SSJPM assumes independence between the tidal and storm surge components, fits a generalised Pareto distribution to the skew surge threshold exceedances, then convolves the probability density functions describing the statistical behaviour of the skew surges and tides [1]. Incorporating historical events into the SSJPM method corresponds to including the historical skew surges within the EVA fit on skew surges, then convolving the probability density functions of the skew surges and tides.

Incorporating historical events into EVA models often leads to higher return levels, especially if the historical events are particularly extreme and occurred close to the start of the systematic data, which is likely to outweigh the uncertainties in the estimates of the magnitudes of the historical events. Several different methods of including historical events have been used in previous literature and there is no scientific consensus over the best practice. In this study, we considered four methodologies described in the following subsections.

[2] https://www.surgewatch.org/events/1921-11-01/
[3] https://www.surgewatch.org/events/1921-12-17/

2.2.1 Concatenation approach

This approach concatenates the historical skew surge events to the start of the measured skew surge dataset and fits a statistical model to the extremes of this concatenated dataset. The main limitation of the method is that it is expected to give values that are unnecessarily conservative because the model understands that more extremes occurred in a shorter time. This is more of a concern when there is a long time gap between the historical events and the start of the observations. The historical events used in this study are up to around 36 years before the start of the 58 years of tide gauge data, so there is a relatively long time gap in this case.

The method is applied in this report and the results are available in Section 2.3.2.1.

2.2.2 Data extension approach

The data extension approach extends the observational data by repeating part or whole of the dataset to cover the dates of the historical storms. The historical skew surges are included at the date they occurred, giving a more accurate temporal distribution of the historical events than the concatenation approach (Section 2.2.1). An EVA model is then fit to the extended data including the historical events. This method assumes the “perception hypothesis” which is the hypothesis that the historical events included are the only ones within the time frame considered that exceed the threshold. Given that the threshold used for this analysis is high (~97th percentile of the tide gauge data), and the historical storms included are all of the Surgewatch storms between 1900-1964 that have been validated in BEEMS report TR322, the perception hypothesis is unlikely to introduce significant error compared to a study of a complete systematic tide gauge dataset since 1900. Furthermore, the more instructive comparison is between this method and the baseline EVA model without including historical storms, where it is clear that this method introduces significant conservatism. This method was used in the BEEMS TR322 report [5] and is implemented in Section 2.3.2.3 in this report.

2.2.3 Monte Carlo approach

The Monte-Carlo approach uses a statistical model fit to the extremes of the observational skew surges to sample an extension to the observational dataset. It fits a new statistical distribution to the extremes of this extended dataset with the historical events included. By repeating this process many times, a range of fits to the extended datasets is established, and thus a range of estimates for each return level can be derived. This range gives a quantification of the uncertainty in each return level. This approach has been used in recent academic literature [10].

For each return period, the mean of the range of return levels derived using the Mote-Carlo approach is expected to align with the point estimate using the data extension approach described in Section 2.2.2. This is because the first model in the Monte-Carlo approach is fit to the same extremes that are repeated in the data extension approach. Because of this, this method has not been applied in this report.

2.2.4 Local credible duration pproach

The local credible duration approach [11] is a first step of a spatial method, called the FAB (Frau, Andreevsky, and Bernardara) method, that includes historical events via regional frequency analysis (RFA) applied on observations [12]. RFA is the estimation of the frequency of extreme events at one site by using data from several other sites. The local credible duration approach defines the credible duration covered by the historical data available (assuming that data are missing) based on the hypothesis that the frequency of exceedances of high skew surge is identical for the observed and the historical data. More precisely, the average number of observed skew surges per year exceeding the threshold is equal to the number of historical skew surges per year over the same threshold. This method has the benefit of avoiding the “perception hypothesis” if there are long records at other sites. However, it requires the analysis of data from many different locations to build up a spatial distribution of extremes. While this may be possible for the Lowestoft location, the return level estimates using the data extension approach provide a sufficient update to the baseline return levels without the need to analyse other data sources beyond the Lowestoft, Sizewell, and Felixstowe comparisons.

2.3 Results

In this section, three results are provided:

- Models A1, A2, and A3 corresponding to an update of [1] EVA for Lowestoft tide gauge for which observations from 1st of January 2019 to the 31st of January 2022 have been added to the period 1964-2019 previously available. The three models, based on different time periods and thresholds, are detailed and compared.
- Model A3-H1: Inclusion of historical data to 1964-2022 Lowestoft sea level observation based on the concatenation approach described in Section 2.2.1.
- Model A3-H2: Inclusion of historical data to 1964-2022 Lowestoft sea level observation based on the data extension approach described in Section 2.2.2.

2.3.1 Return levels for Lowestoft tide gauge data without historical events (models A1, A2, and A3)

In this section, the peak over threshold method is applied on skew surge observations at Lowestoft to fit a generalized Pareto distribution (GPD) on exceedances applying the maximum likelihood estimation included in the *extReme* R package. Firstly, results from [1] are replicated where a threshold of 97% was applied on twice-daily skew surges observed from 1964 to 2019, this corresponds to model A1. The best estimates, the 5th and 95th percentiles for the scale and shape parameters of the associated GPD are provided in Table 4.

Secondly, two tests have been applied on skew surges observations at Lowestoft for the period 1964-2022: (i) model A2 keeping the same threshold of the 97% quantile of the 1964-2019 observations, and (ii) model A3 updating the threshold of the 97% quantile ver the period 1964-2022. Scale and shape parameters best estimates and 5th and 95th percentiles of r spec ive GPD provided in Table 4 are close, which is expected as the variation in the threshold is lower than 1 mm, likely lower than the precision of the tide gauge.

The choice of threshold when applying the peak over threshold method on 1964-2022 skew surge observations is validated by the parameter stability plot (Figure 4 - left) and the mean residual life plot (Figure 4 - right). The orange dashed lines on th se diagnostic plots highlight the range of valid thresholds between 0.4 m and 0.6 m (named u on the x-axis) f r which the changes in the GPD parameters remains small when the threshold varies. We highlight that the EA coastal boundaries modelling report from 2018 [2] does not provide the shape and scale parameters and therefore cannot be compared directly.

Table 4 highlights that including additional observations from 1st January 2021 to 31st January 2022, a period with numerous exceedances above the threshold without experiencing very high skew surge (Section 2.1.1), lead to minor changes in the parameters lower than 0.01 which highlights the robustness of the EVA.

Table 4: Scale and shape parameters of the GPD fits applied to observed skew surges at Lowestoft for 1964-2019 and 1964-2022 periods for models A1, A2 and A3 based on different thresholds, u.

Parameter	**Percentile**	**1964 – 2019** **u = 97%, 0.5035 m** **Model A1 [1]**	**1964 – 31/01/2022** **u = 96.9829%, 0.5035m** **Model A2**	**1964 – 31/01/2022** **u = 97%, 0.5041m** **Model A3**
Scale	5^{th}	0.182	0.182	**0.184**
	50^{th}	0.196	0.197	**0.198**
	95^{th}	0.210	0.210	**0.211**
Shape	5^{th}	-0.02	-0.02	**-0.03**
	50^{th}	0.029	0.025	**0.022**
	95^{th}	0.082	0.076	**0.073**

To assess the quality of the GPD model A3 that fits to the exceedances of skew surge over 1964-2022 with 97% threshold u = 0.5041m, Figure 5 illustrates the quantile-quantile (QQ) plot where the model quantiles fit reasonably well the observed quantiles even if A3 slightly underestimates the two most extremes observations. In addition, Table 5 provides the 10-year to 10,000-year return levels of skew surge at Lowestoft for the three models A1 that corresponds to [1] results, A2 that keep the same threshold of u = 0.5035 m over the period 1964 -2022 and A3 that uses the 97^{th} quantile of 1964-2022 skew surges with u = 0.5041 m. Best estimates (50^{th} quantile) alongside the 5^{th} and 95^{th} quantiles built using delta method are provided (see [1] for more information).

The return periods of the three models are close, showing the robustness of the analysis and the benefit of such a long time series. Model A1 lead to the higher return periods, followed by model A2 and then A3. They are of about 2 cm difference for the 95^{h} quantiles of the 10-year return periods, and about 11 cm for the best estimates of the 10,000-year return levels. We highlight that these differences are slightly higher between model A1 and A2 or A1 and A3, than between A2 and A3. This means that adding 2 years and 1 month of observations has a higher impact than changing the threshold for less than 1 mm. As a conclusion, due to the low variation between A2 and A3 and to keep a physical meaning of the threshold choice of 97^{th} quantile, we recommend using model A3 for the rest of the analysis as an update of the return periods based on observations, even if it orresponds to slightly lower return periods than model A1. For clarity, results related to model A3 are in bold n Table 4, Table 5, and Table 6.

Figure 6 illustrates the hazard curves of GPD model A3 built with threshold of 97% over the period 1964-2022, with the best estimates in central dark line and the 5^{th} and 95^{th} quantile shaded in blue that includes the black dots correspond to the empirical return periods of the observed skew surges.

To complete the results, the SSJPM is applied to estimate return levels of sea level available in Table 6 for model A1 based on [1] and model A3 that corresponds to our recommendation. Best estimates (50^{th} quantile) alongside the 5^{th} and 95^{th} quantiles built using bootstrap are provided (see [1] for more information). Differences of sea level return periods between both models are small (around 11 cm) for the best estimates of the 10,000-year return period, with A3 leading to slightly lower return levels than A1, as 2020-2022 period has recorded slightly lower extreme events than previous years.

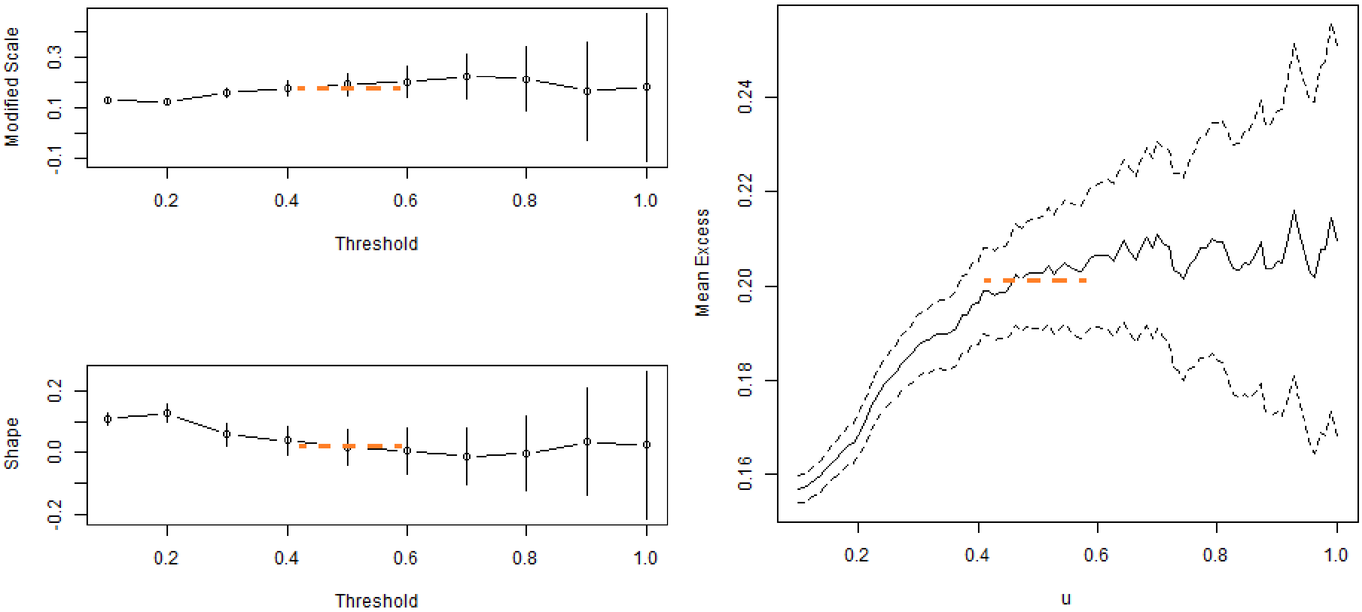

Figure 4: Parameter stability plot (left) and Mean Residual Life plot (right) for skew surge at Lowestoft 1964-2022. Orange dashed lines highlight the range of valid thresholds between 0.4 m and 0.6 m (named u on the x-axis).

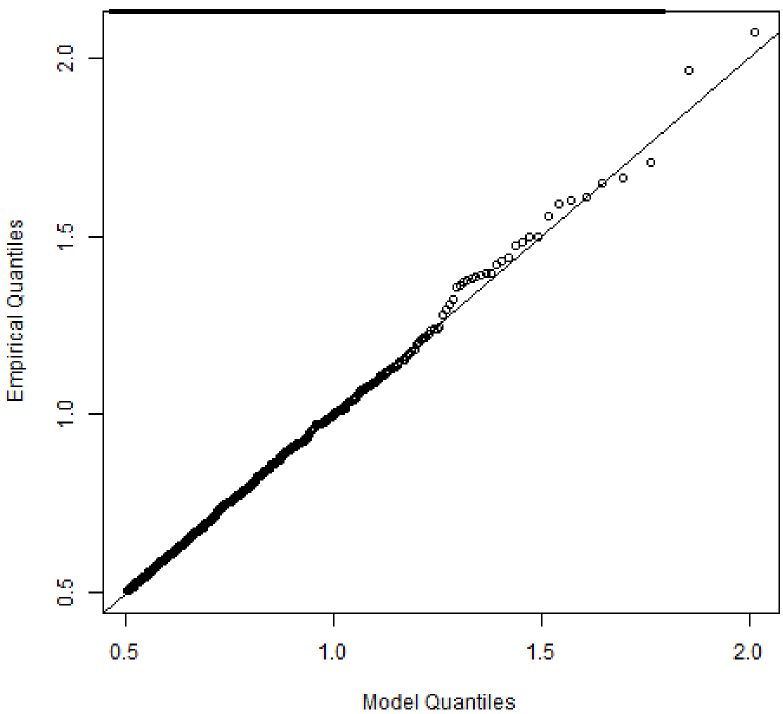

Figure 5: QQ plot comparing the empirical and model quantiles of skew surge at Lowestoft for the GPD model with a threshold of 97% over the period 1964-2022 (0.5041m) - model A3.

Table 5: 5th quantile, best estimates, and 95th quantile of 10-year to 10,000-year return levels of skew surges at Lowestoft for GPD models A1, A2, and A3 based on different periods and thresholds u.

Return period, years	Percentile	Skew surge return level, m 1964 – 2019 u = 97%, 0.5035m Model A1 [1]	1964 – 31/01/2022 u = 0.5035m Model A2	**1964 – 31/01/2022** **u = 97%, 0.5041m** **Model A3**
10	5th	1.52	1.51	**1.51**
	50th	1.64	1.63	**1.63**
	95th	1.76	1.75	**1.74**
100	5th	1.91	1.90	**1.89**
	50th	2.19	2.16	**2.15**
	95th	2.46	2.43	**2.41**
1,000	5th	2.25	2.23	**2.22**
	50th	2.77	2.72	**2.70**
	95th	3.29	3.21	**3.18**
10,000	5th	2.55	2.52	**2.51**
	50th	3.[illegible]0	3.32	**3.29**
	95th	4.24	4.11	**4.06**

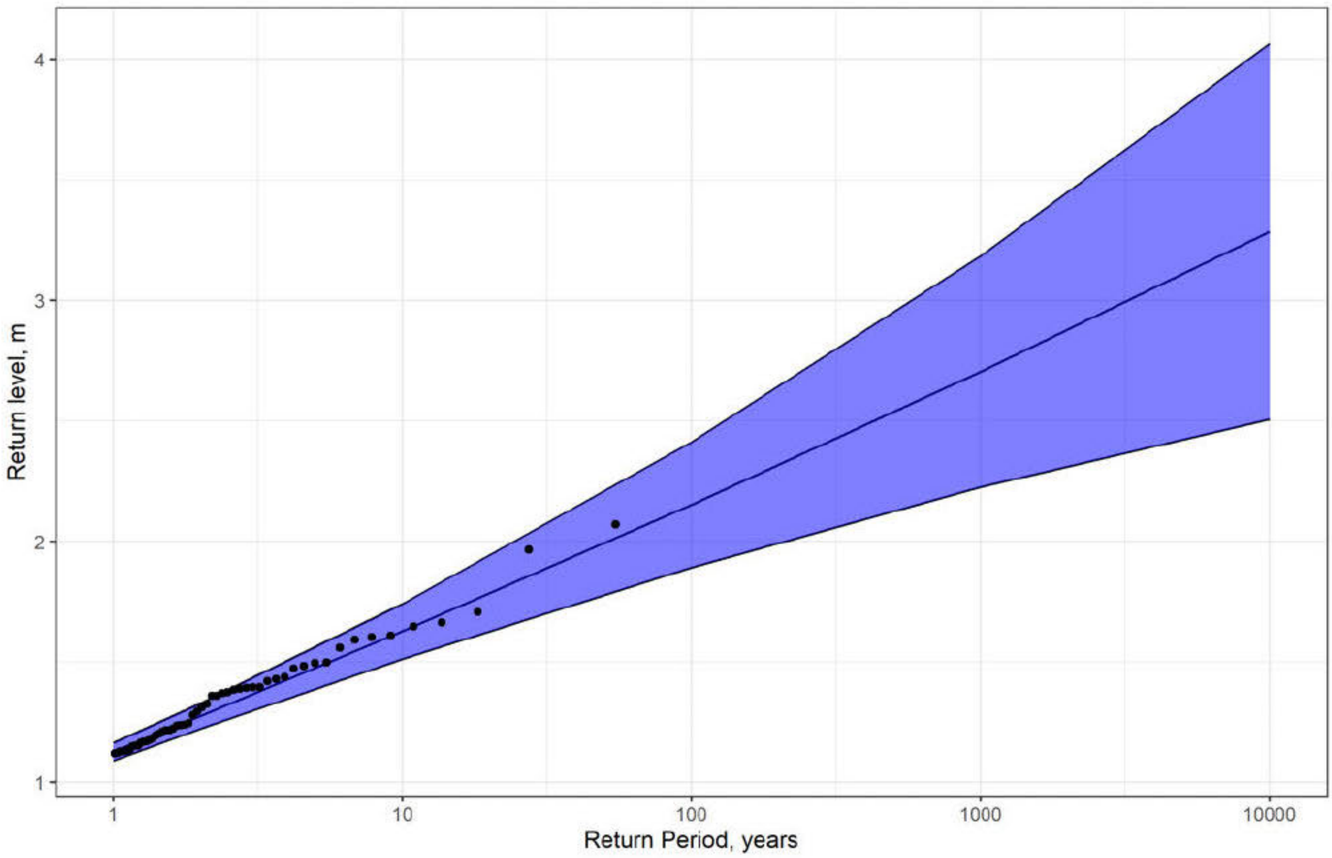

Figure 6: Hazard curves of GPD model A3 built with threshold of 97% over the period 1964-2022, with the best estimates in central dark line and the 5th and 95th quantile shaded in blue. Black dots correspond to the empirical return periods of the observed skew surges.

Table 6: 5th quantile, best estimates and 95th quantile of 10-year to 10,000-year return levels of sea level using SSJPM at Lowestoft for GPD models A1 and A3.

Return period, yea	Percentile	Sea level return level, mOD 1964 – 2019 u = 97%, 0.5035m Model A1 [1]	 1964 – 31/01/2022 u = 97%, 0.5041m Model A3
10	5th	2.46	**2.45**
	50th	2.55	**2.54**
	95th	2.66	**2.65**
100	5th	2.87	**2.85**
	50th	3.10	**3.07**

Return period, years	Percentile	Sea level return level, mOD 1964 – 2019 u = 97%, 0.5035m Model A1 [1]	Sea level return level, mOD 1964 – 31/01/2022 u = 97%, 0.5041m Model A3
	95th	3.32	**3.31**
1,000	5th	3.25	**3.23**
	50th	3.68	**3.61**
	95th	4.13	**4.09**
10,000	5th	3.62	**3.59**
	50th	4.30	**4.19**
	95th	5.07	**5.02**

2.3.2 Return levels including historical events

In this section, we use the A3 baseline model (Section 2.3.1) and apply two methods of adding historical events to the 1964-2022 observations of skew surges and tides to estimate return periods of sea level using the SSJPM:

- Model A3-H1 for the concatenation approach. This is applied first by including only the 1953 historical event and then second for all four historical events.
- Model A3-H2 for the data extension approach.

For comparison purposes, Table 1 provides the 10-year to 100,000-year return levels of sea level at Lowestoft based on the application of the SSJPM to each of these models as well as the A3 model which does not include the historical storms. The quantiles in this table are built using the bootstrapping method.

2.3.2.1 Concatenate 1953 storm only

Firstly, we use a conservative approach of concatenating the 1953 historical event to the start of the Lowestoft tide gauge data, therefore treating this event as though it occurred in 1964. The GPD model that fits this data is named A3-H1-1953. The threshold of 0.5041m is applied, corresponding to the 97th quantile of the 1964-2022 detrended observations. The GPD shape and scale parameters are:

- Scale: 0.195 with the 5th and 95th quantiles of the uncertainty [0.182; 0.209].
- Shape: 0.040 with the 5th and 95th quantiles of the uncertainty [-0.009; 0.090].

The shape parameter for model A3-H1-1953 is slightly more positive than the shape parameter for model A3. This means that the GPD function is slightly more concave, leading to higher return level estimates for long return periods. This is to be expected as a storm larger than all other storms in the tide gauge data has been added.

The skew surge return levels derived using this GPD model are given in Table 7 and the sea level return level estimates calculated using SSJPM with uncertainty percentiles calculated using bootstrapping are given in Table 10.

Table 7: 5th quantile, best estimates, and 95th quantile of 10-year to 10,000-year return levels of skew surges at Lowestoft for model A3-H1-1953.

Return period, years	Percentile	Skew surge return level, m Model A3-H1-1953
10	5th	1.55
	50th	1.67
	95th	1.79
100	5th	1.97
	50th	2.26
	95th	2.54
1,000	5th	2.37
	50th	2.90
	95th	3.43
10,000	5th	2.71
	50th	3.60
	95th	4.50
100,000	5th	3.00
	50th	4.38
	95th	5.75

2.3.2.2 Concatenate four historical storms

Next, we use a more conservative approach of concatenating all four historical events to the start of the Lowestoft tide gauge data. The GPD model that fits this data is named A3-H1. The same threshold of 0.5041m is applied. The GPD shape and scale parameters are:

- Scale: 0.193 with the 5th and 95th quantiles of the uncertainty [0.179; 0.206].
- Shape: 0.069 with the 5th and 95th quantiles of the uncertainty [0.019; 0.120].

The GPD model A3-H1 leads to a more positive shape parameter than the A3 model (see Table 4), which will lead to higher return level. Figure 7 helps to assess the quality of the model A3-H1 where empirical quantiles are compared to the model quantiles. The graph shows that the fit is not very good and that the historical skew surges (2m, 2.10m, 2.25m and 2.5m) are underestimated by the model.

Table 8 and Figure 8 provide the 10-year to 10,000-year return levels of skew surge at Lowestoft based on A3-H1 model with the best estimates (50th quantile) alongside the 5th and 95th quantiles built using the delta method. As expected, this model has much higher return periods than the baseline model without historical storms due to the particularly conservative assumptions of this method. For example, the 10,000-year return level best estimates for A3-H1 model is 4.23m, compared to 3.29m for model A3.The sea level return level estimates with associated uncertainty percentiles are given in Table 10.

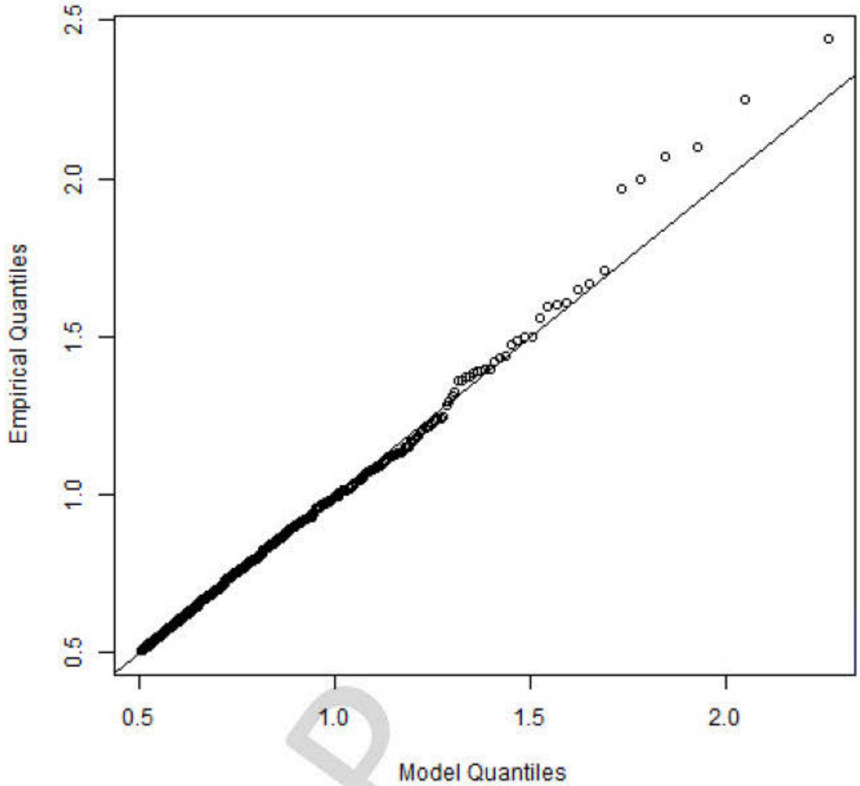

Figure 7: QQ plot compares the empirical q antiles and the model quantiles of skew surge at Lowestoft for the GPD model A3-H1 with a threshold of 97% over the period 1964-2022 (0.5041m).

Table 8: 5th quantile, best estimates and 95th quantile of 10-year to 10,000-year return levels of skew surges at Lowestoft for model A3-H1 including historical data.

Return period, years	Percentile	Skew surge return level, m Model A3-H1
10	5th	1.62
	50th	1.75
	95th	1.89
100	5th	2.12
	50th	2.45

Return period, years	Percentile	Skew surge return level, m Model A3-H1
	95th	2.79
1,000	5th	2.61
	50th	3.27
	95th	3.93
10,000	5th	3.08
	50th	4.23
	95th	5.39

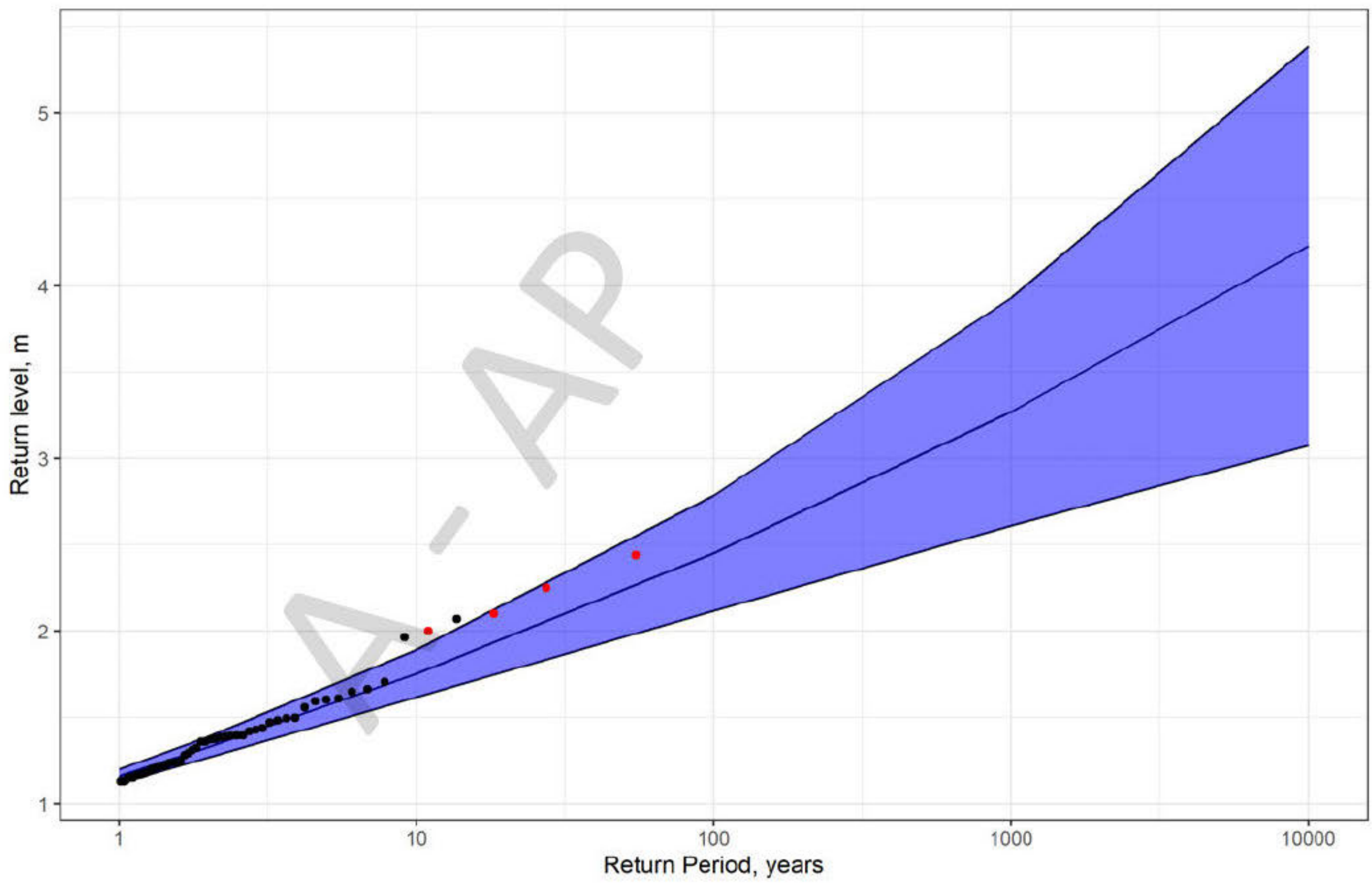

Figure 8: Hazard curves of GPD model A3-H1 built with threshold of 97% over the period 1964-2022, with the best estimates in central dark line and the 5th and 95th quantile shaded in blue. Black and red dots correspond to the empirical return periods of the observed and historical skew surges respectively.

2.3.2.3 Data extension approach

The model fit using the data extension approach is called A3-H2 and is built upon A3 model that uses the threshold of 97th percentile of Lowestoft 1964-2022 observations (u = 0.5041m) and add four historical events within synthetic copy-paste data. The GPD shape and scale parameters are:

- Scale: 0.198 with the 5th and 95th quantiles of the uncertainty [0.187; 0.208].
- Shape: 0.044 with the 5th and 95th quantiles of the uncertainty [0.005;0.082].

The scale parameters are quite close from the model A3-H1, while the shape parameters are in-between the model A3 and A3-H1; therefore, the return periods of skew surge are anticipated to be between model A3 and A3-H1.

Figure 9 helps to assess the quality of the model A3-H2 where empirical quantiles are compared to the model quantiles. When compared to Figure 7 we can see that the A3-H2 GPD fit is better than the A3-H1 fit but it still underestimates the historical data. This can also be seen in Figure 10 which provides the hazard curves of A3-H2 model with empirical return levels of observations and historical in black and red dots respectively.

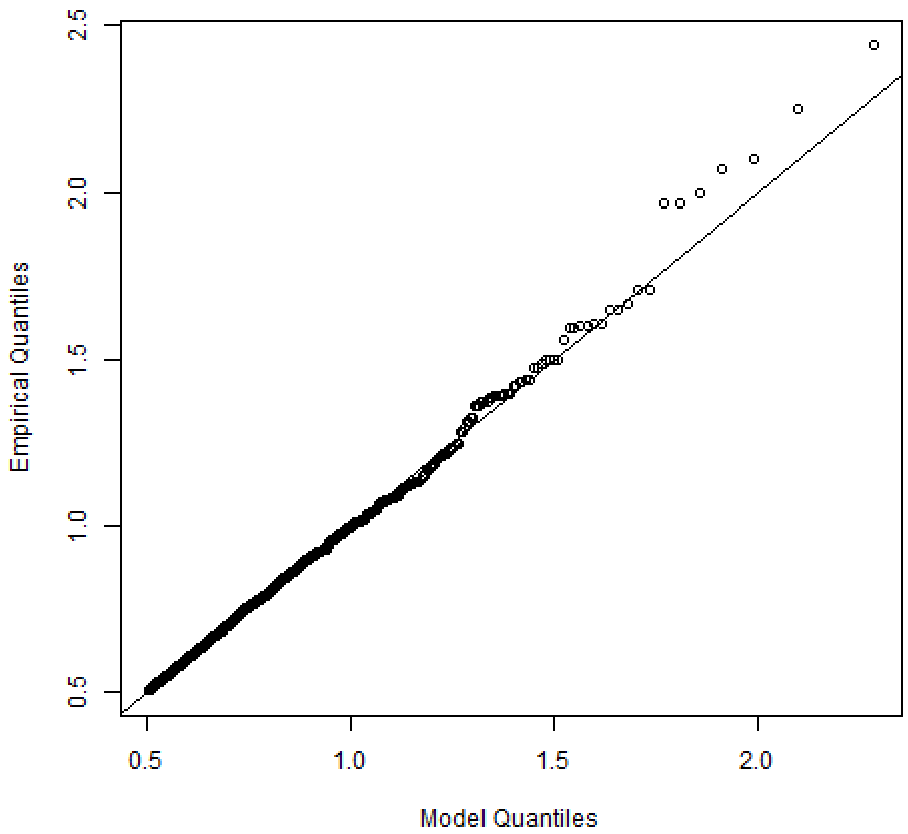

Figure 9: quantile-quantile plot compares the empirical quantiles and the model quantiles of skew surge at Lowestoft for the GPD model A3-H2 with a threshold of 97% over the period 1964-2022 (0.5041m).

Table 9 and Figure 10 provide the 10-year to 10,000-year return levels of skew surge at Lowestoft based on A3-H2 model with the best estimates (50th quantile) alongside the 5th and 95th quantiles built using delta method. The application of the data extension approach to add four historical events to the observed skew surge leads to higher return periods than ignoring the historical events and lead to lower return periods than the concatenation approach. For example, the 10,000-year return level best estimates for A3-H2 model is 3.72m, while it is 4.23m for A3-H1 and 3.29m for model A3.

The sea level return level estimates with associated uncertainty percentiles are given in Table 10. The return levels are compared between the A3 and A3-H2 models in Figure 11.

The variety of models studied in this section show how adding historical storms can significantly increase the estimated return levels, adding a level of conservatism to the baseline results derived using tide gauge data.

Table 9: 5th quantile, best estimates and 95th quantile of 10-year to 100,000-year return levels of skew surges at Lowestoft for model A3-H2

Return period, years	Percentile	Skew surge return level, m Model A3-H2
10	5th	1.61
	50th	1.70
	95th	1.80
100	5th	2.09
	50th	2.31
	95th	2.51
1,000	5th	2.56
	50th	2.98
	95th	3.41
10,000	5th	3.01
	50th	3.72
	95th	4.44
100 000	5th	3.44
	50th	4.54
	95th	5.65

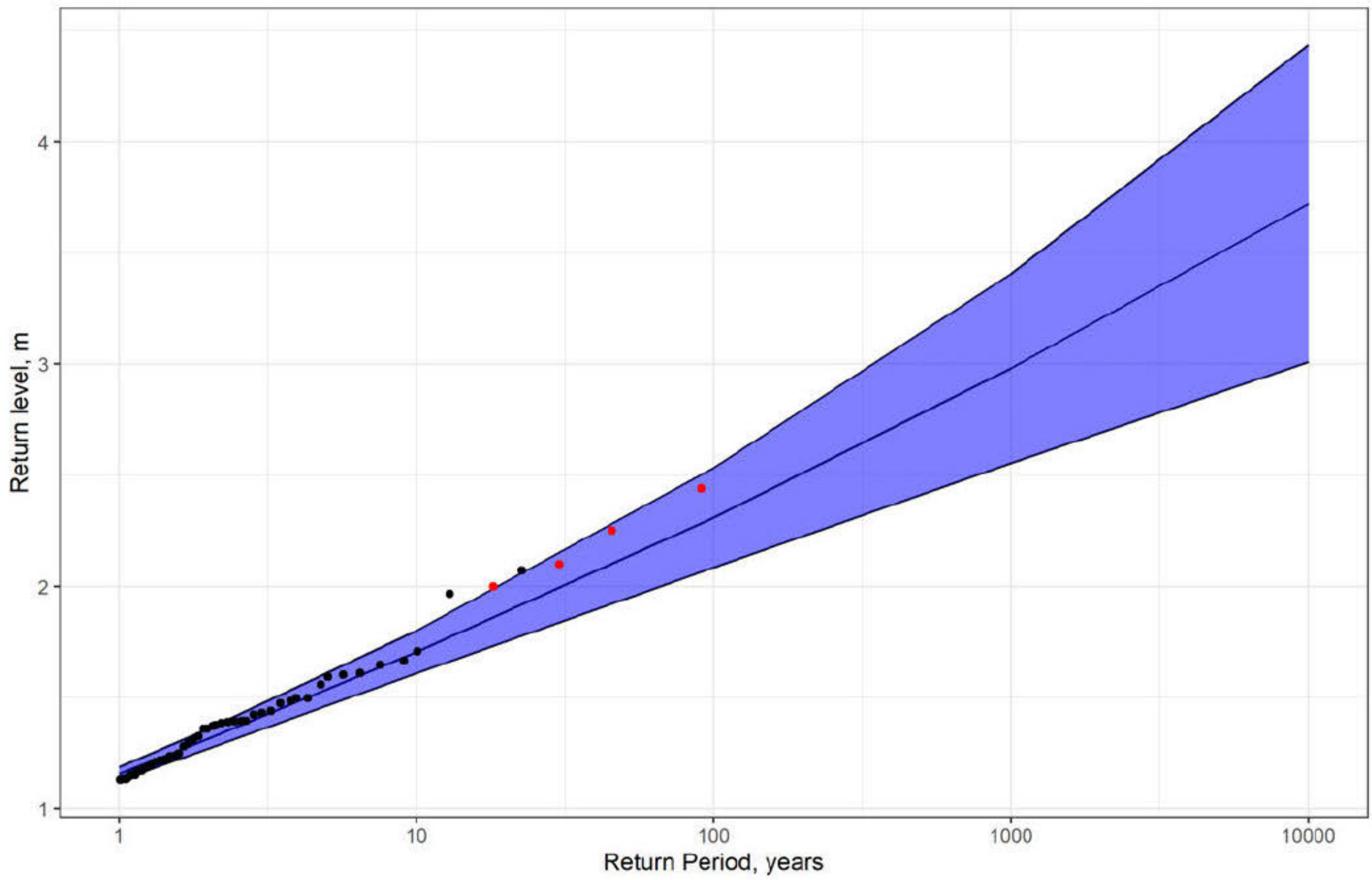

Figure 10: Hazard curves of GPD model A3-H2 built with threshold of 97% over the period 1964-2022, with the best estimates in central dark line and the 5th and 95th quantile shaded in blue. Black dots correspond to the empirical return periods of the observed skew surges and red points to the empirical return levels of the historical data.

Table 10: Sea level return levels estimated using GPD model A3 (no historical events) and three GPD models that incorporate historical data in different ways.

Return period, years	Percentile	Sea level return level, mOD			
		Model A3 - No historical events	Model A3-H1 1953 only	Model A3-H2	Model A3-H1 – 4 events
10	5th	2.45	2.47	2.52	2.54
	50th	2.54	2.58	2.61	2.66
	70th	2.57	-	2.63	-
	84th	2.60	2.65	2.66	2.73
	90th	2.62	-	2.67	-

Return period, years	Percentile	Sea level return level, mOD			
		Model A3 - No historical events	Model A3-H1 1953 only	Model A3-H2	Model A3-H1 – 4 events
	95th	2.65	2.70	2.69	2.79
	97.5th	2.67	-	2.71	-
100	5th	2.85	2.88	3.00	3.05
	50th	3.07	3.16	3.21	3.35
	70th	3.14	-	3.25	-
	84th	3.21	3.32	3.32	3.53
	90th	3.25	-	3.37	-
	95th	3.31	3.45	3.41	3.67
	97.5th	3.35	-	3.47	-
1,000	5th	3.23	3.29	3.48	3.59
	50th	3.61	3.80	3.87	4.15
	70th	3.75	-	3.95	-
	84th	3.89	4.12	4.10	4.54
	90th	3.99	-	4.19	-
	95th	4.09	4.39	4.30	4.81
	97.5th	4.18	-	4.40	-
10,000	5th	3.59	3.69	3.95	4.11
	50th	4.19	4.50	4.61	5.11
	70th	4.42	-	4.74	
	84th	4.66	5.05	5.01	5.80
	90th	4.83	-	5.16	-
	95th	5.02	5.53	5.37	6.40
	97.5th	5.17	-	5.54	-

Return period, years	Percentile	Sea level return level, mOD			
		Model A3 - No historical events	Model A3-H1 1953 only	Model A3-H2	Model A3-H1 – 4 events
100,000	5th	3.90	4.08	4.44	4.67
	50th	4.80	5.27	5.42	6.23
	70th	5.04	-	5.64	-
	84th	5.48	6.12	6.06	7.35
	90th	5.76	-	6.31	-
	95th	6.11	6.94	6.65	8.31
	97.5th	6.47	-	6.97	-

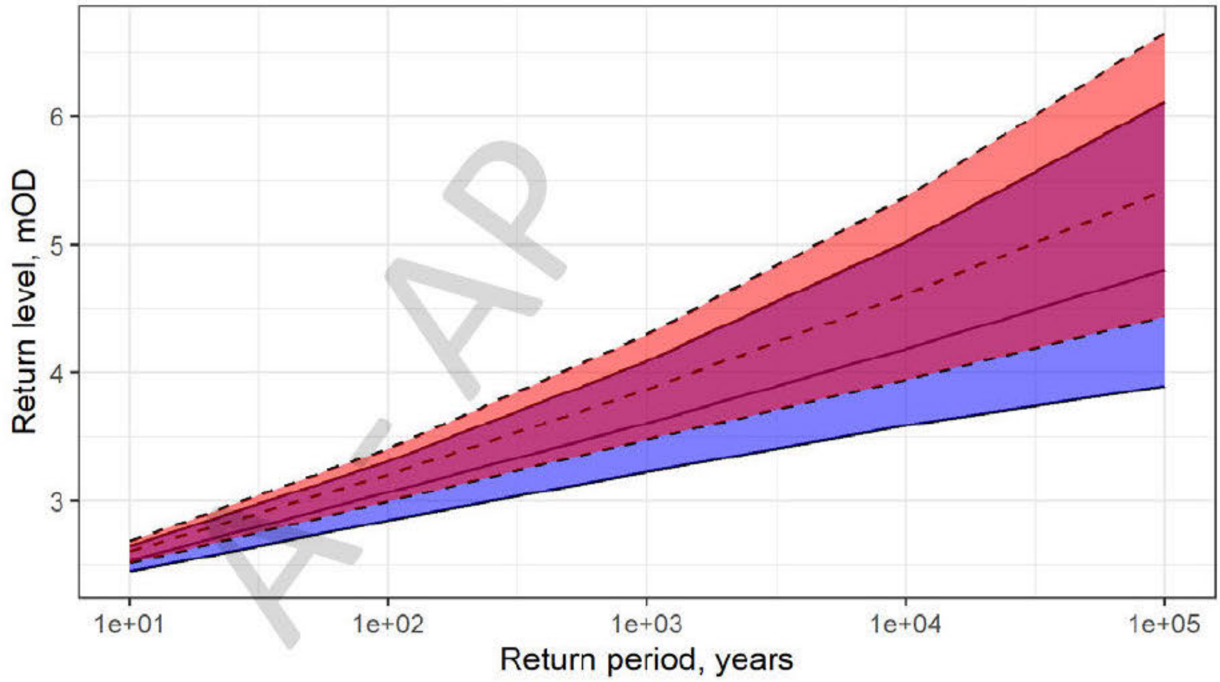

Figure 11: Sea level return level estimates for the A3 model (blue, Lowestoft tide gauge data without historical storms) and the A3-H2 model (red and dashed, Lowestoft tide gauge and four historical storms using the data extension approach). The middle lines for each model are the best estimate and the upper and lower lines for each model are the 5th and 95th percentiles derived using bootstrapping.

3 Deriving intermediate percentiles of EA and Lowestoft tide gauge models

In this section, we compare the uncertainty percentiles in the sea level return levels in the EA Coastal Boundaries model [2] (fit to Lowestoft tide gauge data 1964-2018) with the return levels and associated uncertainties in extreme sea levels calculated in Section 2.3.1 for model A3 (fit to Lowestoft tide gauge data 1964-2022 without historical storms). Results are detailed in Table 11.

The EA model uncertainties are quantified as a best estimate and a 95% confidence interval (i.e. the 2.5th, 50th, and 97.5th percentiles) calculated using bootstrapping. To access uncertainty percentiles between these percentiles, we have fit a normal distribution using maximum likelihood estimate.

There is overall agreement between the two models, even at long return periods and high percentiles. This convergence is to be expected as both models use the same methodology (although possibly a different threshold choice as the EA did not publish this) and overlapping data. The differences in return levels and associated uncertainty percentiles between the Lowestoft tide gauge extrapolations (furthest right column in Table 11) and those in the EA model (third column in Table 11) are due to the additional four years of data used to derive the return levels in this report (1964-2022 rather than 1964-2018). Also, there is likely to be a contribution from the different threshold choice as the 2018 updated version of the EA model does not give the threshold chosen.

Table 11: Sea level return period comparison between EA and EDF approach (model A3)

Return period, years	Percentile	EA model (1964-2018)	Lowestoft tide gauge (1964-2022) Model A3
10	50th	2.56	**2.54**
	70 h	2.59	**2.57**
	84th	2.62	**2.60**
	90th	2.63	**2.62**
	95th	2.65	**2.65**
	97.5th	2.67	**2.67**
100	50th	3.10	**3.07**
	70th	3.17	**3.14**
	84th	3.23	**3.21**
	90th	3.26	**3.25**
	95th	3.31	**3.31**

Return period, years	Percentile	EA model (1964-2018)	Lowestoft tide gauge (1964-2022) Model A3
	97.5th	3.35	**3.35**
1,000	50th	3.69	**3.61**
	70th	3.82	**3.75**
	84th	3.93	**3.89**
	90th	4.00	**3.99**
	95th	4.09	**4.09**
	97.5th	4.17	**4.18**
10,000	50th	4.32	**4.19**
	70th	4.52	**4.42**
	84th	4.70	**4.66**
	90th	4.80	**4.83**
	95th	4.94	**5.02**
	97.5th	5.06	**5.17**
100,000	50th	-	**4.80**
	70th	-	**5.04**
	84th	-	**5.48**
	90th	-	**5.76**
	95th	-	**6.11**
	97.5th	-	**6.47**

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5 Conclusions

EDF R&D UK Centre supports Nuclear New Build in identifying the design of the permanent sea defences for SZC. This includes hard and soft coastal defence features to ensure nuclear safety against sea level flooding. This deliverable provides additional support for extreme sea level characterisation at SZC to supersede and extend the 2020 EDF R&D UK Centre extreme sea level analysis [1].

Firstly, we have updated the extreme value analysis of sea level for the present climate by including new observations of skew surges and tides at Lowestoft, adding observations from 1st of January 2020 to the 31st of January 2022 to the 1964-2019 data previously available. Three models have been applied highlighting that adding two years and one month of observations leads to larger changes in the results than slightly changing the threshold (expected result that illustrates the quality of fit). Here, we recommend using as the Lowestoft baseline the model called A3 that uses the threshold of 97th quantile for the observations period available from 1964 to 2022. Results of return levels of skew surges and sea level are very similar between model A3 and [1], with A3 estimating slightly lower values than [1]. For example, the 10,000-year return level of sea level best estimates and 95th quantiles are respectively 11 cm and 5 cm smaller for model A3 in comparison to [1].

Secondly, we have applied two methods to include four historical events of extreme high sea level between 1900-1964 (start of tide gauge observations at Lowestoft) into the estimation of extreme return levels for the present climate. More specifically, we build two models upon the baseline A3 model. The first model applied is called A3-H1 and uses the concatenation approach that concatenates the historical events to the start of the observed dataset. This leads to overly conservative results as the model reads the historical events as having occurred in 1964 rather than before, artificially shortening the empirical return periods. The second model called A3-H2 uses the data extension approach that better represents the period covered by the historical events. A3-H2 better models the historical events as it reads them as occurring precisely when they occurred in reality. Thus, the model A3-H2 provides conservative results compared to the baseline, without making overly conservative assumptions about he historical data.

To conclude on the benefit of historical data, the application of model A3-H1 and model A3-H2 highlights the need to account for historical events of skew surges and tides when available. The results provide an estimate of high return levels of skew surges and sea levels at Lowestoft and showcase that A3 model based on observations only is not able to provide the complete assessment of the skew surge and high sea level risks for the present climate.

In the third part of the report, we assessed the robustness of both the 2018 EA Coastal Boundaries model and the current analysis by comparing results of 10-year to 10,000-year return periods of sea level for numerous confidence intervals. As expected, the results derived in this report using the baseline model closely match the results in the EA model. The small differences are due to the additional 4 years of data used in this report.

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