Coastal flood boundary conditions for the UK: update 2018

Technical summary report

SC060064/TR6

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Executive summary

This report presents the findings of a project to review and update the extreme sea levels published by the Environment Agency in 2011 as an output from the R&D project, 'Coastal Flood Boundary Conditions for UK Mainland and Islands' (SC060064). The improvements afforded by this project are needed to support successful risk-based flood and coastal erosion risk management, which requires the best available information on coastal flood boundary conditions.

The aims of the update were to provide:

- a consistent set of extreme sea levels around the coasts of England, Wales, Scotland and Northern Ireland
- a means of generating appropriate total storm tide curves for use with the extreme sea levels
- best practice guidance on how to use these new datasets

Work was carried out in 2017 to 2018 to:

- apply new sea level science and improvements to statistical methods to update the existing extreme sea levels
- make use of nearly 10 years of additional observational data recorded at National Tide Gauge Network (NTGN) sites since the original study, supplementary data available at NTGN sites and gauge data provided by other organisations for non-NTGN sites
- extend the locations for which extreme sea levels are provided to include Northern Ireland
- provide extreme sea levels along priority tidal rivers and estuaries

Key outputs included:

- extreme peak sea levels of annual exceedance probability ranging from 1:1 to 1:10,000 (1-year to 10,000-year return period)
- highest astronomical tide and mean high water spring tide conditions
- peak sea level values for the full study area coastline at a spacing of about 2km along the open coast or less in estuaries and harbours (enabling rapid selection of appropriate levels without any need for further interpolation)
- advice on generating appropriate total storm tide curves for use with the extreme sea levels
- extension of the dataset in several key estuaries

The significant enhancements achieved by the project included improved tidal analysis, improved de-trending, an improved statistical model, improved confidence intervals and improved extremal index estimation.

Practical guidance on how to use the new datasets, including a worked example, is given in the user guide accompanying this technical report. Detailed results from the update are given in a series of geographical information system (GIS) shapefiles available on data.gov.uk.

The updated coastal flood boundary database will be used to inform coastal defence strategy, flood mapping and forecasting, and to support policy, implementation and operational decision-making.

Contents

1. Introduction

1.1. Background

Successful risk-based flood and coastal erosion risk management requires the best available information on extreme sea levels (ESLs) required as coastal flood boundary conditions.

In extreme analysis of physical events we are, by definition, often trying to predict an event that has not occurred and indeed may rarely occur. Despite the uncertainties, practitioners require information on ESLs for various purposes, including:

- flood risk mapping
- flood risk assessments
- spatial planning
- coastal flood defence design
- flood warning
- port operations
- infrastructure decisions
- coastal erosion management
- climate change assessments
- informing emergency planning

1.2. About the project

In April 2008, an R&D project (SC060064: Coastal Flood Boundary Conditions for UK Mainland and Islands) was set up by the Environment Agency and the Department for Environment, Food and Rural Affairs (Defra) to develop and apply better methods to update coastal flood boundary datasets, using a longer data record. The aims of the project were to provide:

- a consistent set of ESLs around the coasts of England, Wales and Scotland – replacing the advice given in a Proudman Oceanographic Laboratory report published in 1997 (Dixon and Tawn 1997)
- a means of generating appropriate total storm tide curves for use with the ESLs
- best practice guidance on how to use these new datasets

The findings were reported in Environment Agency (2011).

The project used statistical analysis to extrapolate water levels to higher return periods than observed in the range of data. There were 2 main limitations with this approach.

- The statistical expressions within the model, although well justified, remain theoretical.
- The results from the statistical model, as with other models, depend on the quality and quantity of the data input.

It was therefore recommended that the project be updated regularly to improve the accuracy of the statistical models and so that these remained valid over time with the availability of new, good quality data.

1.3. Update 2018

This report presents the results of the most recent review and update to the ESLs carried out in 2017 to 2018, including details of the additional data, improved scientific methods, and the findings from the ESL and storm tide curve studies. The detailed results are given in geographical information system (GIS) files available on https://environment.data.gov.uk. Practical guidance on how to use the new datasets, including a worked example, is given in the user guide accompanying this report. The original study also provided boundary conditions for extreme swell waves, but these were not replaced for this update.

The improvements afforded by this project are required to support successful risk-based flood and coastal erosion risk management, which requires the best available information on coastal flood boundary conditions.

This project was carried out for the UK Coastal Flood Forecasting partnership, including the Environment Agency, Scottish Environment Protection Agency (SEPA), Natural Resources Wales and the Department for Infrastructure Northern Ireland (DfINI). The work was conducted by a project team led by JBA Consulting, and including Professor Jonathan Tawn of Lancaster University and staff from the National Oceanography Centre (NOC). The project also included extensive consultation and wider involvement with UK practitioners and subject matter experts.

The main objective of the 2018 update was to extend the gauge data records used in the ESL analysis with new data. Since the original study was commissioned in 2008, nearly 10 years of additional observational data have been recorded at gauge sites making up the National Tide Gauge Network (NTGN); these data were available for use in this analysis. The project also used supplementary data available at NTGN sites. Overall, these additional data resulted in relatively significant increases in the length of the data record at many NTGN sites (see Section 2.2).

New sea level science was also available for the 2018 update. Although many of the statistical methods applied during this update were the same as those detailed in Environment Agency (2011), a number of significant improvements were made. These can be summarised as follows and are described in more detail in Section 3:

- **Improved tidal analysis** – improvements to the representation of the base astronomical tide in the analysis and determination of skew surges with explicit calculation of the 18.6-year nodal cycle
- **Improved de-trending** – site-specific de-trending of changes in mean sea level to improve the consistency of levels at each tide gauge
- **Improved statistical model** – improvements to the statistical method to mitigate the need for site-specific changes and ensure a consistent approach that can be applied in the future
- **Improved confidence intervals** – more complete determination of uncertainty (confidence intervals) in the statistical method including the choice of threshold
- **Improved extremal index estimation –** a physically based approach to the determination of the extremal index parameter used to generate the final probabilities of extremes

Another significant change in 2018 was the addition of ESLs to Northern Ireland and along priority tidal rivers and estuaries. Estuary data are often needed in fluvial studies that require an understanding of ESL conditions at the downstream boundary. Estuary locations have also seen significant flooding recent years, such as the Humber Estuary in 2013, and so there is a strong need to understand risk due to ESLs in these locations.

The coastal flood boundary (CFB) database will be used to:

- inform coastal defence strategy, flood mapping and forecasting
- support policy, implementation and operational decision-making

1.4. Study area

The study area for which results are provided encompasses all open coastline around England, Scotland, Wales and Northern Ireland. The following islands are also included:

- Isle of Scilly
- Anglesey
- Scottish Islands of the Firth of Clyde, Hebrides, Orkney and Shetland
- Isle of Man (gauge only)
- Isles of Scilly (gauge only)
- Jersey (gauge only)

1.5. Summary of outputs

Key outputs from the project may be summarised as follows:

- Extreme peak sea levels of annual exceedance probability (AEP) ranging from 1:1 to 1:10,000 AEP (1-year to 10,000-year return period)
- Highest astronomical tide (HAT) and mean high water spring (MHWS) tide conditions
- Peak sea level values are given for the full study area coastline at a spacing of about 2km along the open coast or smaller in estuaries and harbours – this enables rapid selection of appropriate levels without any need for further interpolation
- Advice on generating appropriate total storm tide curves for use with the ESLs
- Extension of the dataset in several key estuaries

1.6. Notes

– Note 1: ESLs are considered accurate to one decimal place

ESLs provided by this project can be considered accurate to one decimal place. Two decimal places have been provided to differentiate between nodes on the chainage. This does not infer greater accuracy and the user should be mindful of this when selecting a node for an ESL.

– Note 2: Extreme sea level values are for still water sea levels only

ESL values include the effects of storm surge and astronomical tides but do not specifically account for any localised increase in sea level that may be induced by onshore wave action, orientation or topography. Two additional effects are of note and can be significant in certain circumstances. Wave set-up is an increase in water level due to on shore wave action (wave set-down is the opposite). Wind set-up is where the local wind shear stress pushes the water level up at the shore (and again set-down is the opposite). Depending on the circumstances these may or may not be well accounted for in the ESL estimates. Tide gauges can be exposed to these effects or sheltered from it.

– Note 3: Definition of annual exceedance probability

AEPs[1] describe the likelihood of being exceeded in any given year. For instance, an AEP of 1% has a chance of being exceeded 1 in 100 in any given year. In coastal design the reciprocal of an AEP is often termed as a 'return period'. An AEP of 1% is equivalent to a return period of 100 years.

– Note 4: How to obtain the data

The data produced by this project can be obtained under Open Government License from https://environment.data.gov.uk/.

– Note 5: Use of tide (only) data

The 2018 updated dataset includes HAT and MHWS tide levels. These are based on interpolated levels at locations between NTGN sites and should be used for flood risk management purposes only. These levels should not be used for navigation purposes.

– Note 6: Base year for levels

The levels are to a base year of 2017. The base year refers to the year for which the levels are valid and takes account of the mean sea level for the year. Modelling required for years other than 2017 should apply corrections for sea level rise.

[1] The AEPs in this study were determined from peaks-over-threshold analyses and are different to those generated from an annual maximum series for high percentage AEPs (Flood Estimation Handbook, Volume 3, p. 64). If they are to be used in conjunction with fluvial flow estimates in estuarine regions, the fluvial flow estimates for high percentage AEPs should also be determined using a peaks-over-threshold analysis.

– Note 7: Datum for levels

The return levels presented in this report are generally relative to the main tide gauge benchmark, which has a fixed height relative to Ordnance Datum Newlyn (ODN) and Ordnance Datum Belfast (in Northern Ireland). Sites relative to local datums include Stornoway, Lerwick, St Mary's and Isle of Man (Port Erin local OD).

ODN is referred to here as the height above mean sea level at Newlyn from 1950 to 1968. Comparisons of the return levels can only be made with other data relative to the same datum (that is, ODN). Heights measured using a GPS can be converted to ODN via the spatial surface of the transformation model OSGM15, or previously OSGM02.

– Note 8: Estuary, harbour, loch, loughs and tidal river levels

The CFB 2018 estuary and tidal river levels are based on the interpolation of modelled levels including defences and so do not necessarily represent the scenario in which there are no flood defences. Flood defences can constrain coastal flood waters, resulting in elevated water levels upstream. Similarly, levels based on gauge analysis at upstream locations represent the scenario in which defences exist

Results were taken from the modelling of extreme coastal events only. A background fluvial flow may have been included such as the index flood QMED, but the results do not include any joint probability of extreme fluvial and coastal event modelling. Provision for fluvial events should be considered in addition to the levels provided in study.

All levels derived using this method are labelled 'ESTUARY_' in the Location field of the shapefile CFB_Extreme_Sea_Levels_Estuary_2018.shp available on data.gov.uk.

As improved modelling becomes available following this 2018 update, the CFB 'ESTUARY' levels may be subject to review and further updates. The models in this 2018 update also do not include all models available at the time of this report was written. Detailed models have been included as a priority in regions of particular interest. Further locations will be added in the future.

– **Note 9: Confidence intervals**

The confidence levels presented in this report and in the shapefile of 2km return levels (CFB_Extreme_Sea_Levels_2018.shp or CFB_Extreme_Sea_Levels_Estuary_2018.shp in estuaries) take account of the uncertainty associated with the skew surge joint probability statistics only. Uncertainty relating to the accuracy of the CS3X model interpolation, 2km interpolation and tidal prediction is not included. Additional uncertainty due to model inaccuracies should be considered for points labelled 'ESTUARY_', which were derived using local models.

2. Data

2.1. Sources

Tide gauge data used for the determination and validation of ESLs, and the extension of ESLs into estuaries, tidal rivers, lochs, loughs and harbours, include:

- gauge data from the UK NTGN, owned and operated by the Environment Agency, and obtained from the British Oceanographic Data Centre (BODC; part of NOC)
- gauge data supplied by the Environment Agency, SEPA, Natural Resources Wales and DfINI for this project

Third party tide gauge data were kindly supplied by the following organisations:

- Forth Ports
- NOC
- BODC
- UK Hydrographic Office

Figure 2.1 shows a map of all the gauges for which ESLs were estimated in the 2018 update and the supplementary gauges used to extend the ESLs into estuaries, tidal rivers, harbours, sea lochs and loughs.

Maps in Appendix A show the locations of all the estuaries, tidal rivers, lochs, loughs and harbours for which ESLs have been projected using gauge or model data.

Appendix B presents all the tide gauge data, with details of their ownership and the periods of data coverage.

MHWS and HAT for all tide gauges were obtained from:

- Admiralty Tide Tables
- National Tidal and Sea Level Facility

Regionally specific coastal model data were used to supplement tide gauges to allow the ESL estimates to be projected into estuaries, tidal rivers, lochs, loughs and harbours.

Model data were supplied by the Environment Agency, SEPA, Natural Resources Wales and DfINI. Where possible, models of sufficient quality, as assessed by other studies, were used.

Appendix C describes all the regionally specific coastal models.

Appendix D lists all the estuary and harbour models used.

Figure 2.1: Tide gauges for which ESLs were calculated and which provided the basis for subsequent interpolation with the numerical model

2.2. Tide gauge data for ESL analysis, extension and validation

The tide gauge dataset used in the determination of the ESLs for the 2018 update includes 46 NTGN gauges and 7 non-NTGN gauges. This is 6 NTGN and 3 non-NTGN gauges more than used for the original project (Environment Agency 2011). These are new gauges that either became operational after 2009, are in Northern Ireland or for which sufficient data were not previously available.

Where possible, data records have also been extended to the end of 2016 to include gauge data collected during the severe coastal flood events of 2013 and 2014. In addition, some gaps in records up to 2008 (as used in Environment Agency 2011) and in the data up to 2016 have been filled using data salvaged from supplementary instruments at the gauge location.

Appendix B summarises the increases in data coverage at all NTGN gauges through extension of records to the end of 2016 and through filling data gaps using data from alternative instruments.

All NTGN data obtained from the BODC undergo rigorous routine quality checking before release. This results in the flagging of questionable or missing observations; no data values are altered or removed during this process.

All non-NTGN data have undergone some level of quality checking, either by the gauge owners prior to data being obtained and/or solely for the purposes of the current study during time series preparation. Time series data for all non-NTGN gauges were plotted for every year and inspected for the presence of:

- missing data
- data spikes, where the water level is recorded as being erroneously high or low
- datum shifts, where the water level undergoes a step change from one mean level to another
- datum drifts, where the mean water level shows an apparent increase or decrease over a period of time

Where a datum shift was identified and the new datum known, an appropriate correction was made. However, unknown datum shifts were not estimated; any affected observations were set to missing, along with any erroneous data spikes.

The completeness of data records for all NTGN and all non-NTGN gauges used in the ESL analysis is summarised in Appendix B.4.

In addition to the NTGN and non-NTGN gauges used in the ESL analysis, non-NTGN tide gauges were also used for:

- the extension of ESLs into estuaries, tidal rivers, lochs, loughs and harbours
- validation of ESLs

These gauges have undergone quality checks, as applied to those gauges used in the ESL analysis.

Appendix B.2 contains a list of the non-NTGN tide gauge data used for the extension of ESLs into estuaries, tidal rivers, lochs, loughs and harbours, and for validation of ESLs, their ownership and the periods of data coverage.

2.3. Model data for interpolation of ESLs along coastlines

As in Environment Agency (2011), the NOC operational continental shelf tide-surge (CS3X) model was used to allow the ESLs calculated at tide gauges to be interpolated along the coastline between gauge locations. This model has a spatial resolution of 1/9° latitude by 1/6° longitude (approximately 12km).

The CS3X model was forced with meteorological data from the European Centre for Medium-Range Weather Forecasts global re-analysis dataset, ERA40 (Uppala et al. 2005). The ERA40 dataset was produced by running a weather forecasting model using the weather conditions observed at the time. This dataset provides consistent representation of the state of the atmosphere for a 40-year period at a spatial resolution of 1° latitude and longitude. Mean sea level pressure and wind components at a height of 10m above the surface from the ERA40 dataset are provided as surface boundary conditions to the CS3X model. At the open boundaries of the CS3X model, the 26 largest tidal constituents are provided as tidal input.

The digital General Bathymetric Chart of the Oceans (GEBCO) data are used as the fixed bed bathymetry for the CS3X model. This dataset is maintained by BODC on behalf of the International Hydrographic Organisation and the Intergovernmental Oceanographic Commission of the United Nations Educational Scientific and Cultural Organisation. Higher resolution bathymetry datasets have been incorporated into the GEBCO dataset by BODC.

Although the CS3X model includes the entire coastline considered in this project in its domain, a separate, higher resolution model was used for the north-east Irish Sea. The approach is identical to that used in Environment Agency (2011). A two-dimensional (2-D) depth-averaged version of the Princeton Ocean Model, with a spatial resolution of approximately 200m along the coastline was used in this region. The higher spatial resolution allows for a more accurate representation of the local wetting and drying processes associated with the tidal flats that characterise this region. The surface boundary conditions are the same ERA40 data used for the CS3X model. The ocean boundary conditions are the tide and surge provided by a coarser resolution continental shelf model (similar to the CS3X model). The fixed bed bathymetry for the higher resolution model domain was enhanced using cross-section sonar data from Morecambe Bay supplied by Lancaster City Council and light ranging and detection (LiDAR) data provided by the Environment Agency for intertidal areas (that were dry during data acquisition).

Appendix C provides further information on both the models used for the interpolation of ESLs along coastlines. Further information on the CS3X model and validation of the model is given in O'Neill et al. (2016).

2.4. Model data for the extension of ESLs into estuaries, tidal rivers, lochs, loughs and harbours

For this 2018 update, the ESLs were extended along estuaries, tidal rivers, lochs, loughs and harbours. This was primarily accomplished using regionally specific coastal models which extend further into these tidal areas, and at higher spatial resolution, than the UK-wide tide-surge model CS3X. The CS3X model, run at a spatial resolution of approximately 12km, may not be able to easily resolve upstream tidal areas characterised by narrow straits and channels (for example, upstream in the Severn Estuary).

Extreme water levels were derived in upstream tidal areas by interpolation of the levels output from detailed local models. Many coastal models were commissioned around the UK before and after the publication of Environment Agency (2011), including in England, Wales, Scotland and Northern Ireland.

All Environment Agency coastal modelling for England were assessed in Environment Agency (2016) and classified according to quality. Model quality was assessed in this study by considering:

- model input data
- model resolution
- suitability
- how recent the modelling was carried out

Only those models considered suitable for design (class A), appraisal (class B) or strategic (class C) were used in the extension of ESLs into estuaries. Models with classification 'U' were considered potentially out-of-date or low quality.

For Scotland, the extension of levels within sea lochs, loughs, firths and estuaries is based largely on the findings of a project which collated existing estuarine modelling and gauge data in Scotland (SEPA 2013). Relationships between upstream and downstream levels were derived from both model results and gauge level-to-level comparisons (similar to those detailed in Section 2.5 of this report). Where no modelling or gauge data were available, the relationships from similar or nearby estuaries were applied instead. Further details are available in the project report (SEPA 2013).

Additional modelling was carried out to refine levels for the Loch Linnhe system as part of this project.

In Northern Ireland, several models were available in Carlingford Lough, Strangford Lough and Lough Foyle.

Many models were also available for estuaries in Wales.

A summary of all the estuaries, tidal rivers, lochs, loughs and harbours for which ESLs have been provided – and the models used – is given in Appendix D.. Studies that were readily available were used along with a risk-based prioritisation for incorporation at this stage.

Estuaries and regions provided with new ESLs are shown in Appendix A.

2.5. Level-to-level comparisons

Gauges with a record length of less than 10 years can be used in analysis of extremes, but are likely to be associated with very large uncertainty. These sites are best used in the validation of other ESL sites and in deriving interpolation factors from CFB sites.

Sites where gauge data were used for level-to-level comparison include 3 sites in Wales (Llanelli, Pontycob and Tintern) and one site in Northern Ireland (Victoria Lock).

Level-to-level comparison was also used in previous studies (for example, south-west England estuaries, Environment Agency 2008) and some sites in the 2013 Scottish National Coastal Flood Hazard Mapping (SEPA 2013). Further details on this approach can be found in Appendix H.

3. Method of deriving ESLs

3.1. Introduction

This section provides an overview of the methods used to derive ESLs around the UK coast. A more comprehensive description of the methodology is given in Appendix E.

ESL analysis requires the estimation of return periods beyond the length of the data record being studied. It is therefore difficult to determine these levels from empirical analysis. Statistical models, however, can be used to provide estimates of these levels by using the behaviour of the observed data to extrapolate to return periods corresponding to unobserved levels. But while these models are state-of-the-art and well justified, they are based on theoretical arguments and therefore may not fully capture the long-term distribution of physical processes. Nonetheless, efforts have been made to incorporate physical and spatial information into the statistical analysis with the aim of producing realistic ESLs for a range of return periods.

Statistical analysis of ESLs was performed for the 53 tide gauge sites detailed in Section 2, the results of which are outlined in Section 4.

3.2. Skew surge

ESLs around the UK are experienced as some combination of tidal high water with a further contribution from storm surges. High surges arise as a result of low atmospheric pressure and increasing strength of surface winds, which can lead to an increase in sea levels.

Skew surge, the difference between the maximum water level and predicted astronomical high tide, is a more reliable indicator of meteorological impacts on sea level than the non-tidal residual (Figure 3.1:), which may contain errors due to timing or harmonic prediction.

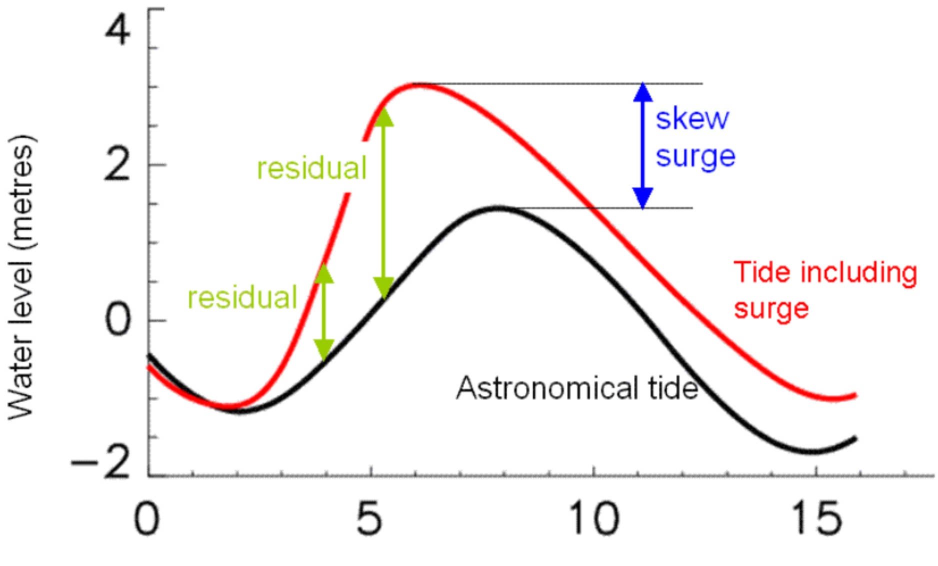

Figure 3.1: Skew surge is the difference between maximum sea level observed during a tidal cycle and the predicted high water

3.3. Skew surge joint probability method (SSJPM)

For the UK, both tides and storm surges are potentially large and therefore a joint probability approach provides the optimum statistical analysis of ESLs. The fundamental advantage of a joint probability approach is that it provides separate analyses for the (distribution of) the deterministic tide and the stochastic, weather-driven storm surge components of sea level. This approach has been adopted previously for the UK (see, for example, Tawn and Vassie 1989). A review of the advantages of joint probability techniques is given by Haigh et al. (2010).

Central to this class of statistical models is the assumption that meteorological processes are independent of tidal processes, and so any surge can occur on any tide. As discussed in Section 3.2, skew surge is the most representative indicator of the meteorological impact on sea level. The SSJPM models the joint probability of skew surge and predicted high tide.

Exploratory analysis of skew surges shows that the distribution is bell-shaped and symmetric around zero. Combinations of large skew surges and high tides can lead to very large sea levels, but combinations of large skew surges and low tides (and vice versa) can also lead to potentially impactful sea level events. Many of the skew surges generating ESLs are observed in the upper tail of the distribution. By definition, extreme events are rare, and thus empirical estimates of return levels are highly uncertain and restricted to the range of the data.

The generalised Pareto distribution (GPD) (Davison and Smith 1990) is instead fitted to the upper tail above some suitably chosen high threshold (Figure 3.2). The GPD is an asymptotically justified limit model, but is used here as a finite sample approximate model for excesses above a high threshold. The GPD is a three-parameter model, the most important to consider being the shape parameter, which controls the rate of extrapolation to high return periods.

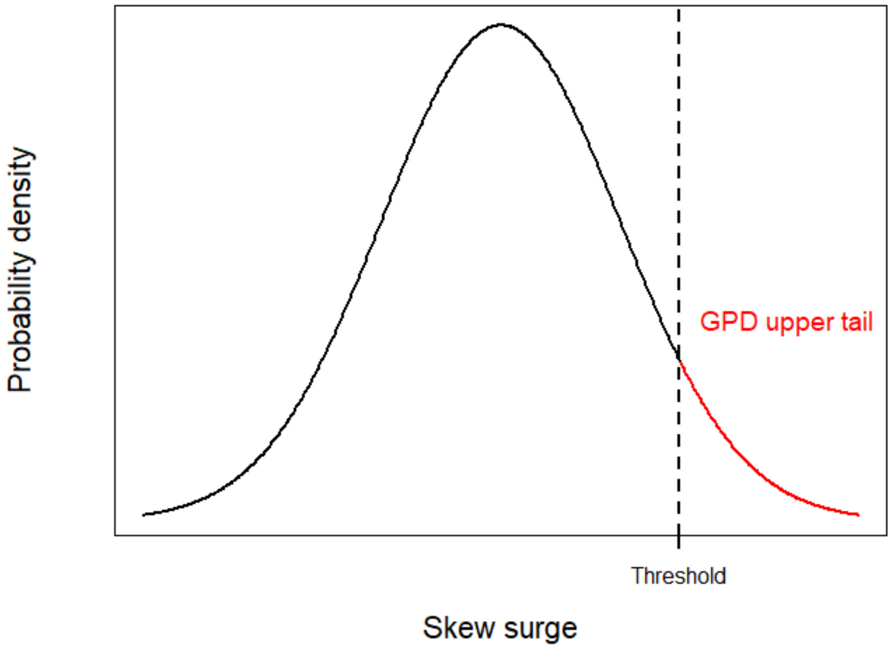

Figure 3.2: Schematic of the GPD as a model for the upper tail of skew surge defined above a suitably high threshold

In contrast, peak tide levels are deterministic quantities and are constrained by astronomical forcing. Thus, the tails of peak tide are well represented and a GPD model is not needed. Instead the 18.6-year lunar nodal cycle was derived and peak tides were extracted.

Before the analysis was performed, the data at each tide gauge were de-trended to take account of changes in mean sea level. A linear trend was estimated using a combination of local and regional physical information that constrained the trend to spatially consistent values. This allowed trends to be estimated with greater confidence at gauges with a short record length. A linear trend was used in preference to a varying trend because:

- many tide gauges are too short to detect any acceleration in changes in mean sea level

- the acceleration is highly uncertain at gauges with longer record length, such as Newlyn and Belfast

The distributions of peak tide and skew surge were used to estimate the joint probability of all possible peak tide/skew surge combinations that result in ESLs. This is estimated assuming independence between skew surge and peak tides; Williams et al. (2016) discuss the validity of this assumption.

The statistical model assumes that peak water levels in each tidal cycle are independent. However, storm systems lasting multiple days can produce a series of successive ESLs. A correction factor, known as the extremal index, is used to account for this dependence in the estimation of return levels. A more comprehensive description of the SSJPM methodology is provided in Appendix E.

3.4. Improvements on Environment Agency (2011)

Several significant improvements to the SSJPM methodology are made compared with that detailed in Environment Agency (2011). These are described in detail in Appendix E, but can be summarised as follows.

- Tidal analysis was improved by consistent estimation of tidal constituents and peak tides, and improved determination of skew surges with explicit calculation of the 18.6-year nodal cycle.
- Estimation of the long-term trend in mean sea level at each tide gauge was improved by using both local and regional information as indicators.
- Statistical estimation of the shape parameter in the skew surge distribution was improved. The parameter at each tide gauge was constrained by the mean and spread of the unconstrained estimates at all gauges in the UK. This ensured smooth spatial variations of this quantity and produced physically plausible values at each tide gauge at high return periods. This treatment is implemented as part of the model fitting rather than the post-hoc smoothing in Environment Agency (2011).
- There was improved threshold selection and incorporation of the uncertainty behind this selection in the estimation of confidence intervals.
- A physically based approach was adopted for the determination of the extremal index, which accounts for differing levels of dependence at different levels.

3.5. Interpolation of return levels around the coastline of the UK using a numerical model

The SSJPM provided a set of return levels corresponding to specified return periods at the 53 tide gauges. As tide gauges are typically separated by many kilometres of coastline, a suitable interpolation method is required. Simulations from a numerical ocean model were used to:

- provide estimates of extreme water levels between the tide gauge sites
- guarantee a consistent methodology around the entire coastline, including complex topographic regions

By using a numerical model to interpolate dynamically, the correct spatial behaviour of the tide and storm surges in between tide gauge locations is represented.

The UK operational tide-surge model was used, at 12km resolution (CS3X), forced by the European Centre for Medium-range Weather Forecasting (ECMWF) ERA40 meteorological re-analysis (at 1º resolution). Although numerical models tend to underestimate the actual values of ESLs when forced by coarse resolution meteorological data, they do provide the correct spatial dynamical response. When suitably combined with tide gauge calibration, they can provide return levels at locations for which no observations exist. However, the coarse resolution of the model means it is less likely to simulate ESLs accurately in narrow straits and channels.

Model estimates at all coastal locations were derived. For all mainland coastal model cells (a total of 339), the return levels were then corrected using a weighted interpolation approach. This ensures that the spatial properties of both the tide and storm surges influence the correction more than distance. For the model cells corresponding to tide gauges, differences between modelled and observed extreme levels were calculated.

At all cells between tide gauge locations, the model levels were then adjusted using a weighted fraction of the differences at the 2 nearest gauge sites. The 339 files of corrected model return levels were supplied in the same format as ESLs estimated directly at the 53 tide gauge sites. For island locations that are ungauged, the tide gauge most likely to be representative for each stretch of island coastline was identified. The adjustment from that tide gauge was used to adjust the model levels of the islands.

As well as the SSJPM (median) return level estimates, 95% confidence intervals were interpolated around the coastline using the same approach.

3.6. Further interpolation of return levels using the north-east Irish Sea model and interpolation to 2km

A coastal trend line was set up around the UK with chainages running clockwise from an origin at Newlyn. The trend line was set a little offshore from the coast so that distances would not become unduly distorted by small coves and promontories not resolvable by CS3X model resolution, as would be the case, for example, if mean low water mark was used. Chainage points were set at 2km intervals. The trend line is shown on the figures in Appendix A.

The CS3X model provided return period ESLs at intermediate points between primary sites broadly at 12km spacing. A finer resolution was obtained by interpolating spatially to 2km. This was generally based on inverse distance weighting methods but with the following 3 notable exceptions.

- Levels in north-west England were based on the high resolution north-east Irish Sea model to best represent the spatial changes along this highly variable, shallow coastline.
- Levels were interpolated using observed trends in high tides where there was an inconsistency between high tide levels and the estimated ESLs. Areas include the region around Workington, the Pentland Firth, Margate, Eastbourne and the Severn Estuary.
- Levels at Liverpool and Immingham were considered locally higher due to their estuary locations. This is reflected in the interpolation to 2km and informed by the north-east Irish Sea and MHWS tide levels. Previously, only Hilbre had been used instead of Liverpool to reflect the ESLs along the open coastline.

Where levels were interpolated based on validation against high tide levels, this sometimes resulted in larger changes in return levels than those due to additional data and updated statistics at UK NTGN sites. Areas of note include the Severn Estuary, Pentland Firth, Mersey Estuary, Solway, Llŷn Peninsula and Chesil Beach. The levels obtained in Environment Agency (2011) had not previously been compared with high tide levels, but this has provided an important validation of interpolated 2km levels, especially in areas where rapid changes occur within the 12km CS3X model resolution.

3.7. Extension of ESLs into estuaries, tidal rivers, lochs, loughs and harbours

Environment Agency (2011) did not provide an extension of the ESLs into tidal areas where the CS3X model would not easily resolve the region. ESLs at upstream locations are important for those conducting fluvial studies where extreme high tide levels may have an impact on upstream river levels.

To maintain consistency between fluvial and coastal extreme water levels and to reduce the need for re-calculation, the ESLs from the tide gauge and the national tidal and surge model were extended to upstream locations. These take account of extreme water levels due to coastal drivers only. Additional joint probability analysis will be required to predict the risks due to both ESLs and high flows in upstream locations.

Upstream levels were derived from applying relationships between upstream and open coastal water levels. These relationships were either taken from existing modelling or derived using level-to-level analysis. A similar approach was taken in the Scottish National Coastal Flood Hazard Mapping study (SEPA 2013). Levels derived using this approach are labelled 'ESTUARY_' in the shapefile CFB_Extreme_Sea_Levels_Estuary_2018.shp available on data.gov.uk.

3.7.1. Local modelling

Regionally specific coastal models were used to provide these extended ESLs. For many models, a range of extreme water levels are applied at the open coastal boundary to derive levels along estuaries and further upstream. These scenarios often include climate change scenarios and overtopping of defences, in which case the extreme sea levels may cease to increase with rising ESLs as water exits the tidal river channel and flows over the floodplain. These model results build a complex picture of the response of upstream estuary levels to extreme sea level drivers and geometric factors, which is difficult to determine using statistical extrapolation alone.

For new CFB 2018 levels already within the range modelled in the regional models, upstream levels were derived by interpolation. A relationship between the modelled downstream and upstream water levels was determined for each upstream location.

For new CFB 2018 levels outside of those previously modelled by the regional models, the water level relationship between upstream and downstream levels was extended to interpolate new upstream levels. The difference between the highest modelled water levels at the downstream and upstream locations was considered constant for higher water levels. Where this assumption could not be considered valid, no upstream levels were included in the CFB 2018 update. Similarly, the difference between the lowest modelled water levels at downstream and upstream locations was considered constant for lower water levels. Where available, HAT was used to determine appropriate differences between lower water levels.

Where one-dimensional (1-D) modelled levels were used in the interpolation, the CFB 2018 estuary level locations correspond with the exact 1-D model output locations unless very small changes in water level are observed. In these cases, similar 1-D model levels were excluded from the CFB 2018 outputs to avoid duplication. Where 2-D modelled levels were used in the interpolation, CFB 2018 estuary levels are provided at locations to well represent changes along the channel. Between these location points, the levels may be interpolated between the closest upstream and downstream points. In the case of the Northern Ireland lough models, only the original model output locations were used in the 2018 CFB and no spatial interpolation was performed. There was not enough information on the spatial variation expected in the loughs to assume the interpolation should be linear between points.

All interpolated model levels included in CFB 2018 are based on defended modelling. The levels are therefore valid for the current national coastal defences, but will require updating as new defences are developed and new modelling becomes available. The CFB 2018 estuary levels do not necessarily represent the case in which there are no flood defences, often required for flood risk management, as flood defences can constrain coastal flood waters resulting in elevated water levels upstream.

As improved modelling becomes available following this 2018 update, the CFB 'ESTUARY' levels may be subject to review and further updates. In addition, the models in this 2018 update do not include all available models at the time of writing this report. Detailed models have been included as a priority in regions of particular interest. Further locations will be added in future.

3.7.2. Level-to-level analysis

At 4 locations in Wales and Northern Ireland, the ESLs were extended to upstream locations using level-to-level analysis of gauge data. Empirical evidence suggests that the rate of extrapolation at neighbouring gauges is approximately linear. This linear relationship was fitted to quantiles above 95% between an upstream gauge and a neighbouring gauge where ESLs had been derived using the SSJPM. Through this linear model, the return levels derived from the SSJPM are used to predict the levels at the upstream gauges. More details of this approach and derived water levels can be found in Appendix H.

4. Results and validation

4.1. Extreme sea levels

For most sites in Environment Agency (2011), the ESLs in the 2018 update have not changed significantly. Differences of less than 0.1m are not considered significant as these are within the accuracy of ESL estimation. Only Mumbles (+0.10m), Newport (-0.10m) and Stornoway (-0.14m) have changes larger than a magnitude of 0.1m in the 5-year return period water levels. Table 4.1 lists those locations with changes larger than a magnitude of 0.1m for the 200-year return period water levels.

ESL estimates for return periods between 1 and 10,000 years are provided in Table 4.2; the 2.5% and 97.5% confidence levels are given in Table 4.3 and Table 4.4 respectively. The ESLs and associated confidence levels are also provided in a shapefile available on data.gov.uk.[2] Plots of ESLs and return periods at individual tide gauge sites are presented in Appendix F. These plots show the 2018 updated CFB return levels, corrected to a base year of 2017, and the confidence levels against the levels in Environment Agency (2011).

Table 4.1: Largest changes in the 1 in 200 year return period from Environment Agency (2011)

Gauge site	Change in 1 in 200-year from Environment Agency (2011)
Mumbles	0.17m
Newport	-0.10m
Cromer	-0.19m
Barmouth	0.14m
Felixstowe	-0.18m

Few changes were expected in low return periods such as the 5-year, as these events are well represented in the recorded data with most gauge records exceeding 20 years. The larger differences at Mumbles, Newport and Stornoway are likely to be the result of changes in de-tiding or de-trending, which were both updated for this study. Both de-tiding and de-trending will affect skew surge throughout the gauge record. Changes to the extremal index may also be a factor.

Larger changes to the 200-year return period are more likely to be the result of changes due to the addition of new data. Most of the larger changes for this return period are observed in the south-east England tidal gauges. The December 2013 event is likely to have had some effect on the skew surge GPD fit in this region, where the skew surge also makes up a significant portion of the total sea level. However, these changes are small relative to those observed due to the addition of data when using other methods such as the generalised extreme value of annual maximum (AMAX GEV) for extreme sea level estimation. This shows that the SSJPM is relatively robust to the addition of new extreme event data and that ESLs are well predicted.

The confidence widths in this 2018 update generally increased compared with Environment Agency (2011), though typically only by a few percent. Confidence intervals were expected to widen for most sites and return periods following the introduction of an additional but genuine uncertainty (that is, the choice of threshold).

As with other studies (for example, some climate projections), an increased level of understanding does not necessarily reduce the confidence intervals. For this update, any reduction in uncertainty due to improved record length at gauge sites is offset by the improved methodology. Future updates using the current methodology and with further increases in record lengths at tide gauges are likely to lead to a slight narrowing of the uncertainty bands.

[2] CFB_Extreme_Sea_Levels_2018.shp or CFB_Extreme_Sea_Levels_Estuary_2018.shp in estuaries

Appendix E.6 contains a summary of the return level confidence interval estimation methodology used in this update and how this changed from that used in Environment Agency (2011).

Levels for estuaries, tidal rivers, harbours, sea lochs and loughs were generally derived from model data summarised in Appendix D and included in the shapefile provided (CFB_Extreme_Sea_Levels_Estuary_2018.shp). Levels derived for some additional upstream gauges in estuaries and sea loughs are analysed and presented in Appendix H.

Table 4.2: CFB 2018 update median level estimates

Site	Return period (years)														
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
St Helier*	6.21	6.29	6.38	6.45	6.52	6.54	6.61	6.65	6.68	6.72	6.75	6.78	6.80	6.85	6.93	7.20
Newlyn	3.11	3.18	3.26	3.33	3.39	3.41	3.47	3.50	3.52	3.56	3.58	3.60	3.61	3.65	3.70	3.88
St Mary's*	3.41	3.48	3.56	3.61	3.67	3.69	3.74	3.77	3.79	3.82	3.84	3.86	3.87	3.90	3.96	4.11
Padstow	4.56	4.63	4.73	4.79	4.85	4.87	4.93	4.96	4.99	5.02	5.05	5.07	5.08	5.13	5.19	5.42
Ilfracombe	5.43	5.51	5.61	5.68	5.75	5.77	5.85	5.89	5.92	5.96	5.99	6.01	6.03	6.09	6.17	6.45
Hinkley Point	7.05	7.14	7.25	7.34	7.44	7.47	7.57	7.63	7.67	7.73	7.78	7.82	7.85	7.93	8.06	8.54
Avonmouth	8.11	8.22	8.37	8.49	8.61	8.65	8.79	8.86	8.92	9.01	9.07	9.12	9.16	9.27	9.43	10.05
Newport	7.45	7.56	7.70	7.81	7.92	7.96	8.07	8.14	8.20	8.27	8.33	8.37	8.41	8.52	8.67	9.25
Mumbles	5.51	5.62	5.77	5.88	5.98	6.02	6.13	6.19	6.23	6.30	6.34	6.38	6.40	6.48	6.59	6.99
Milford Haven	4.20	4.29	4.40	4.49	4.57	4.60	4.68	4.73	4.76	4.81	4.84	4.87	4.89	4.95	5.04	5.33
Fishguard	3.10	3.17	3.26	3.33	3.40	3.42	3.49	3.52	3.55	3.59	3.62	3.64	3.65	3.70	3.77	3.99
Barmouth	3.46	3.59	3.75	3.87	3.99	4.03	4.14	4.21	4.26	4.33	4.38	4.42	4.45	4.54	4.67	5.09
Holyhead	3.37	3.44	3.55	3.62	3.70	3.72	3.79	3.84	3.87	3.91	3.94	3.96	3.98	4.03	4.10	4.35
Llandudno	4.70	4.78	4.90	4.98	5.06	5.09	5.17	5.22	5.25	5.30	5.33	5.36	5.38	5.44	5.53	5.81
Hilbre	5.24	5.34	5.47	5.57	5.66	5.69	5.78	5.84	5.87	5.92	5.96	5.99	6.01	6.08	6.17	6.50
Liverpool	5.44	5.56	5.73	5.86	5.98	6.03	6.16	6.24	6.29	6.37	6.42	6.46	6.50	6.60	6.73	7.19
Port Erin*	3.27	3.36	3.48	3.57	3.66	3.69	3.78	3.83	3.87	3.92	3.95	3.98	4.00	4.07	4.15	4.44
Heysham	5.86	5.99	6.16	6.29	6.42	6.46	6.59	6.67	6.72	6.80	6.86	6.90	6.93	7.03	7.17	7.63
Workington	5.09	5.21	5.35	5.47	5.58	5.61	5.73	5.79	5.84	5.91	5.95	5.99	6.02	6.11	6.22	6.62
Portpatrick	2.82	2.92	3.06	3.15	3.25	3.28	3.37	3.43	3.47	3.52	3.56	3.59	3.61	3.68	3.78	4.09
Millport	2.67	2.79	2.96	3.09	3.22	3.26	3.39	3.47	3.52	3.60	3.65	3.69	3.73	3.83	3.97	4.44
Port Ellen	1.45	1.56	1.70	1.81	1.91	1.94	2.04	2.10	2.14	2.20	2.24	2.27	2.30	2.37	2.47	2.81
Tobermory	2.98	3.09	3.23	3.34	3.45	3.48	3.59	3.65	3.69	3.76	3.80	3.84	3.87	3.95	4.06	4.43

Site	Return period (years)														
	1	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Ullapool	3.22	3.32	3.44	3.53	3.62	3.65	3.74	3.78	3.82	3.87	3.90	3.92	3.94	4.00	4.08	4.34
Stornoway*	2.89	2.97	3.07	3.14	3.22	3.24	3.31	3.35	3.37	3.41	3.44	3.46	3.47	3.52	3.58	3.78
Kinlochbervie	3.17	3.28	3.42	3.52	3.62	3.65	3.74	3.80	3.84	3.90	3.94	3.97	3.99	4.06	4.16	4.46
Lerwick*	1.50	1.54	1.60	1.65	1.69	1.71	1.75	1.77	1.79	1.81	1.83	1.84	1.85	1.88	1.91	2.02
Wick	2.40	2.48	2.57	2.64	2.71	2.73	2.79	2.83	2.85	2.88	2.91	2.93	2.94	2.98	3.04	3.21
Moray Firth	2.85	2.92	3.01	3.08	3.14	3.16	3.22	3.26	3.29	3.32	3.35	3.37	3.39	3.43	3.50	3.71
Clachnaharry	3.15	3.23	3.34	3.43	3.52	3.55	3.64	3.69	3.73	3.79	3.83	3.86	3.88	3.95	4.05	4.38
Aberdeen	2.69	2.77	2.86	2.93	3.00	3.02	3.09	3.13	3.15	3.19	3.22	3.24	3.25	3.30	3.36	3.58
Grangemouth	3.92	4.01	4.13	4.22	4.32	4.35	4.45	4.51	4.56	4.62	4.66	4.70	4.73	4.81	4.93	5.37
Leith	3.37	3.45	3.56	3.63	3.71	3.73	3.81	3.85	3.88	3.93	3.96	3.98	4.00	4.06	4.14	4.41
North Shields	3.21	3.29	3.40	3.48	3.56	3.59	3.68	3.73	3.77	3.82	3.85	3.89	3.91	3.99	4.08	4.42
Whitby	3.36	3.45	3.57	3.67	3.77	3.80	3.90	3.96	4.00	4.07	4.11	4.15	4.18	4.26	4.37	4.81
Immingham	4.17	4.27	4.42	4.53	4.65	4.68	4.80	4.88	4.93	5.00	5.06	5.10	5.14	5.24	5.38	5.92
Cromer	3.07	3.19	3.35	3.48	3.61	3.65	3.79	3.88	3.93	4.02	4.08	4.13	4.17	4.29	4.45	5.03
Lowestoft	2.02	2.17	2.38	2.55	2.72	2.77	2.93	3.03	3.10	3.2	3.27	3.32	3.37	3.50	3.69	4.31
Felixstowe	2.68	2.81	2.97	3.11	3.24	3.29	3.43	3.52	3.58	3.68	3.74	3.79	3.82	3.95	4.12	4.77
Sheerness	3.70	3.81	3.96	4.08	4.21	4.25	4.37	4.45	4.51	4.59	4.65	4.70	4.74	4.85	5.01	5.59
Dover	3.80	3.91	4.06	4.17	4.29	4.33	4.44	4.51	4.56	4.63	4.68	4.72	4.75	4.84	4.97	5.39
Newhaven	3.87	3.94	4.04	4.12	4.20	4.22	4.30	4.35	4.38	4.43	4.46	4.49	4.51	4.57	4.66	4.96
Portsmouth	2.55	2.63	2.73	2.80	2.87	2.89	2.96	3.00	3.03	3.07	3.10	3.12	3.14	3.19	3.25	3.49
Bournemouth	1.40	1.47	1.56	1.63	1.69	1.71	1.78	1.81	1.84	1.88	1.90	1.93	1.94	1.99	2.06	2.28
Weymouth	1.82	1.89	1.99	2.05	2.12	2.15	2.22	2.26	2.28	2.32	2.35	2.37	2.39	2.44	2.51	2.76
Exmouth	2.76	2.84	2.95	3.03	3.10	3.13	3.20	3.24	3.27	3.31	3.34	3.36	3.37	3.42	3.48	3.66
Devonport	2.95	3.02	3.11	3.18	3.25	3.27	3.34	3.38	3.40	3.44	3.47	3.49	3.51	3.55	3.62	3.84

Site	Return period (years)															
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Belfast	2.16	2.26	2.39	2.49	2.60	2.64	2.74	2.80	2.85	2.91	2.96	2.99	3.02	3.11	3.23	3.69
Portrush	1.61	1.71	1.83	1.92	2.00	2.03	2.12	2.17	2.21	2.26	2.29	2.32	2.35	2.41	2.50	2.78

Notes: Levels are given in metres Ordnance Datum (mOD) unless stated and are correct to base year 2017. Sites marked with * are referenced to a local datum.

Table 4.3: CFB 2018 update return level – 2.5% confidence bounds

Site	Return period (years)															
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
St Helier*	6.21	6.28	6.37	6.44	6.50	6.52	6.59	6.62	6.65	6.69	6.71	6.73	6.74	6.79	6.85	7.02
Newlyn	3.10	3.17	3.25	3.31	3.36	3.38	3.43	3.46	3.48	3.50	3.52	3.54	3.55	3.58	3.62	3.76
St Mary's*	3.40	3.46	3.54	3.59	3.64	3.66	3.71	3.73	3.75	3.77	3.79	3.80	3.81	3.83	3.86	3.95
Padstow	4.55	4.62	4.71	4.77	4.83	4.85	4.90	4.93	4.95	4.98	5.00	5.01	5.03	5.06	5.10	5.25
Ilfracombe	5.42	5.50	5.59	5.66	5.73	5.75	5.82	5.85	5.88	5.92	5.94	5.95	5.97	6.01	6.06	6.22
Hinkley Point	7.04	7.13	7.24	7.32	7.40	7.42	7.50	7.55	7.57	7.61	7.64	7.66	7.68	7.73	7.79	7.99
Avonmouth	8.10	8.21	8.35	8.45	8.56	8.59	8.70	8.76	8.80	8.86	8.91	8.94	8.96	9.04	9.14	9.45
Newport	7.44	7.54	7.67	7.76	7.85	7.88	7.97	8.03	8.06	8.12	8.15	8.18	8.20	8.26	8.35	8.61
Mumbles	5.49	5.60	5.73	5.83	5.93	5.96	6.04	6.09	6.12	6.16	6.19	6.22	6.24	6.28	6.35	6.55
Milford Haven	4.19	4.27	4.38	4.46	4.53	4.56	4.63	4.68	4.71	4.75	4.78	4.80	4.82	4.87	4.92	5.07
Fishguard	3.08	3.15	3.24	3.31	3.37	3.39	3.45	3.48	3.51	3.54	3.56	3.58	3.59	3.63	3.68	3.84
Barmouth	3.44	3.56	3.71	3.81	3.90	3.93	4.01	4.05	4.08	4.12	4.15	4.17	4.19	4.24	4.31	4.52
Holyhead	3.35	3.43	3.52	3.59	3.66	3.68	3.74	3.77	3.80	3.83	3.85	3.87	3.88	3.92	3.97	4.12
Llandudno	4.69	4.77	4.87	4.95	5.02	5.04	5.11	5.15	5.17	5.21	5.23	5.24	5.26	5.30	5.35	5.48
Hilbre	5.23	5.32	5.44	5.53	5.61	5.63	5.71	5.75	5.78	5.82	5.85	5.88	5.89	5.94	6.00	6.15
Liverpool	5.43	5.54	5.69	5.80	5.91	5.94	6.04	6.10	6.13	6.20	6.24	6.27	6.29	6.36	6.45	6.67
Port Erin*	3.25	3.34	3.46	3.54	3.62	3.64	3.72	3.76	3.78	3.82	3.84	3.86	3.87	3.91	3.96	4.12

Site	Return period (years)															
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Heysham	5.85	5.97	6.13	6.26	6.38	6.41	6.53	6.60	6.64	6.70	6.75	6.78	6.81	6.88	6.97	7.27
Workington	5.08	5.18	5.32	5.43	5.53	5.56	5.65	5.71	5.74	5.79	5.83	5.85	5.87	5.93	6.00	6.22
Portpatrick	2.80	2.89	3.01	3.10	3.18	3.21	3.28	3.33	3.35	3.40	3.42	3.45	3.46	3.51	3.57	3.76
Millport	2.62	2.74	2.88	2.98	3.08	3.11	3.20	3.26	3.30	3.35	3.38	3.41	3.43	3.49	3.57	3.81
Port Ellen	1.38	1.47	1.58	1.65	1.72	1.74	1.80	1.83	1.85	1.88	1.90	1.91	1.93	1.96	2.00	2.14
Tobermory	2.96	3.06	3.19	3.28	3.37	3.40	3.48	3.53	3.56	3.61	3.64	3.66	3.68	3.73	3.79	3.99
Ullapool	3.20	3.30	3.42	3.50	3.59	3.61	3.69	3.73	3.76	3.80	3.83	3.86	3.87	3.92	3.99	4.18
Stornoway*	2.88	2.96	3.06	3.13	3.19	3.21	3.27	3.31	3.33	3.37	3.39	3.41	3.42	3.46	3.50	3.63
Kinlochbervie	3.14	3.24	3.36	3.46	3.54	3.57	3.65	3.70	3.73	3.77	3.79	3.81	3.83	3.87	3.94	4.12
Lerwick*	1.48	1.53	1.59	1.63	1.67	1.68	1.71	1.73	1.75	1.76	1.77	1.78	1.79	1.81	1.84	1.91
Wick	2.39	2.46	2.55	2.61	2.67	2.69	2.74	2.77	2.79	2.82	2.84	2.86	2.87	2.90	2.95	3.08
Moray Firth	2.83	2.90	2.98	3.03	3.08	3.10	3.14	3.16	3.18	3.20	3.21	3.22	3.23	3.25	3.28	3.36
Clachnaharry	3.13	3.21	3.32	3.39	3.47	3.49	3.56	3.60	3.62	3.66	3.68	3.70	3.72	3.76	3.82	4.01
Aberdeen	2.68	2.75	2.84	2.90	2.96	2.98	3.03	3.07	3.09	3.12	3.14	3.15	3.16	3.20	3.24	3.39
Grangemouth	3.90	3.98	4.09	4.16	4.23	4.26	4.33	4.36	4.39	4.43	4.45	4.47	4.48	4.52	4.58	4.74
Leith	3.36	3.44	3.53	3.60	3.67	3.68	3.75	3.78	3.81	3.84	3.86	3.88	3.90	3.93	3.98	4.14
North Shields	3.20	3.27	3.37	3.45	3.52	3.54	3.61	3.65	3.69	3.73	3.75	3.78	3.80	3.85	3.91	4.13
Whitby	3.35	3.43	3.54	3.61	3.69	3.72	3.80	3.84	3.87	3.91	3.94	3.96	3.98	4.03	4.10	4.31
Immingham	4.16	4.26	4.39	4.50	4.60	4.63	4.73	4.79	4.83	4.89	4.93	4.96	4.98	5.05	5.15	5.45
Cromer	3.05	3.16	3.30	3.40	3.50	3.54	3.63	3.69	3.73	3.78	3.82	3.84	3.86	3.93	4.02	4.29
Lowestoft	1.98	2.13	2.30	2.44	2.57	2.61	2.74	2.80	2.85	2.91	2.95	2.98	3.01	3.10	3.21	3.57
Felixstowe	2.62	2.72	2.84	2.93	3.01	3.04	3.12	3.17	3.20	3.24	3.28	3.30	3.32	3.38	3.45	3.69
Sheerness	3.67	3.78	3.91	4.02	4.11	4.14	4.23	4.28	4.31	4.35	4.38	4.40	4.42	4.46	4.53	4.71
Dover	3.78	3.89	4.03	4.13	4.24	4.27	4.36	4.40	4.43	4.47	4.50	4.52	4.54	4.58	4.64	4.83

Site	Return period (years)															
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Newhaven	3.85	3.92	4.02	4.09	4.15	4.17	4.24	4.28	4.30	4.34	4.37	4.39	4.41	4.45	4.51	4.72
Portsmouth	2.54	2.61	2.70	2.76	2.83	2.84	2.90	2.93	2.95	2.98	3.00	3.01	3.02	3.05	3.09	3.21
Bournemouth	1.38	1.44	1.53	1.59	1.64	1.66	1.71	1.75	1.77	1.80	1.82	1.83	1.85	1.88	1.92	2.06
Weymouth	1.80	1.87	1.95	2.01	2.07	2.09	2.15	2.18	2.20	2.23	2.26	2.27	2.28	2.32	2.36	2.51
Exmouth	2.74	2.82	2.92	3.00	3.06	3.08	3.14	3.17	3.19	3.22	3.24	3.26	3.27	3.30	3.34	3.47
Devonport	2.93	3.00	3.09	3.15	3.21	3.22	3.27	3.30	3.33	3.35	3.37	3.38	3.40	3.43	3.47	3.61
Belfast	2.14	2.23	2.34	2.42	2.51	2.53	2.60	2.63	2.66	2.69	2.71	2.73	2.74	2.78	2.82	2.97
Portrush	1.58	1.67	1.77	1.85	1.92	1.94	2.00	2.03	2.05	2.09	2.11	2.13	2.14	2.18	2.22	2.37

Notes: Levels are given in metres Ordnance Datum (mOD) unless stated and are correct to base year 2017. Sites marked with * are referenced to a local datum.

Table 4.4: CFB 2018 update return level – 97.5% confidence bounds

Site	Return period (years)															
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
St Helier*	6.22	6.29	6.39	6.46	6.54	6.57	6.66	6.71	6.75	6.80	6.84	6.88	6.90	6.99	7.12	7.72
Newlyn	3.11	3.18	3.27	3.34	3.40	3.42	3.49	3.52	3.55	3.59	3.62	3.64	3.66	3.71	3.77	4.02
St Mary's*	3.42	3.48	3.56	3.62	3.69	3.70	3.77	3.80	3.83	3.87	3.89	3.91	3.93	3.98	4.05	4.33
Padstow	4.57	4.64	4.74	4.81	4.88	4.91	4.98	5.03	5.06	5.11	5.15	5.18	5.21	5.31	5.44	6.04
Ilfracombe	5.44	5.53	5.63	5.70	5.78	5.81	5.89	5.93	5.97	6.02	6.06	6.10	6.12	6.20	6.31	6.77
Hinkley Point	7.06	7.15	7.29	7.39	7.51	7.56	7.71	7.82	7.88	7.99	8.07	8.15	8.22	8.44	8.74	10.03
Avonmouth	8.13	8.25	8.42	8.55	8.71	8.77	8.95	9.08	9.18	9.33	9.44	9.54	9.62	9.85	10.21	11.80
Newport	7.46	7.58	7.73	7.87	8.04	8.10	8.30	8.43	8.53	8.69	8.81	8.91	8.99	9.22	9.57	11.15
Mumbles	5.53	5.65	5.81	5.92	6.04	6.08	6.22	6.31	6.37	6.47	6.54	6.61	6.65	6.80	7.01	7.86
Milford Haven	4.21	4.30	4.42	4.51	4.61	4.65	4.75	4.82	4.87	4.93	4.99	5.03	5.06	5.16	5.31	5.87
Fishguard	3.10	3.17	3.27	3.35	3.42	3.45	3.54	3.59	3.63	3.68	3.72	3.75	3.77	3.85	3.96	4.39

Site	Return period (years)															
	1	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Barmouth	3.55	3.66	3.83	3.97	4.11	4.16	4.33	4.43	4.51	4.64	4.72	4.78	4.84	5.00	5.23	6.18
Holyhead	3.40	3.48	3.58	3.65	3.73	3.76	3.84	3.89	3.93	3.98	4.02	4.05	4.08	4.16	4.26	4.66
Llandudno	4.72	4.81	4.93	5.02	5.12	5.16	5.26	5.32	5.37	5.44	5.49	5.54	5.57	5.67	5.81	6.35
Hilbre	5.29	5.39	5.52	5.62	5.71	5.74	5.86	5.93	5.99	6.07	6.13	6.17	6.21	6.32	6.48	7.16
Liverpool	5.47	5.61	5.80	5.96	6.14	6.20	6.41	6.54	6.64	6.78	6.89	6.98	7.06	7.28	7.60	8.93
Port Erin*	3.29	3.39	3.53	3.63	3.74	3.78	3.90	3.98	4.03	4.11	4.16	4.21	4.25	4.36	4.54	5.16
Heysham	5.91	6.04	6.21	6.34	6.48	6.53	6.69	6.78	6.85	6.95	7.03	7.09	7.14	7.28	7.49	8.28
Workington	5.11	5.23	5.39	5.51	5.65	5.70	5.84	5.93	5.99	6.08	6.16	6.22	6.28	6.43	6.67	7.61
Portpatrick	2.84	2.95	3.10	3.21	3.34	3.38	3.50	3.58	3.64	3.73	3.79	3.84	3.88	3.99	4.15	4.76
Millport	2.71	2.85	3.04	3.20	3.37	3.43	3.61	3.74	3.82	3.94	4.02	4.09	4.14	4.30	4.54	5.59
Port Ellen	1.52	1.64	1.82	1.95	2.10	2.16	2.33	2.44	2.51	2.61	2.69	2.76	2.81	2.96	3.18	3.99
Tobermory	3.02	3.13	3.32	3.48	3.65	3.71	3.90	4.02	4.11	4.24	4.34	4.42	4.49	4.68	4.96	6.07
Ullapool	3.23	3.33	3.46	3.56	3.66	3.69	3.79	3.85	3.89	3.95	4.00	4.04	4.06	4.15	4.26	4.69
Stornoway*	2.90	2.98	3.09	3.17	3.25	3.27	3.35	3.40	3.43	3.48	3.52	3.54	3.57	3.63	3.73	4.08
Kinlochbervie	3.19	3.31	3.47	3.59	3.72	3.76	3.93	4.03	4.10	4.21	4.29	4.34	4.39	4.53	4.73	5.52
Lerwick*	1.52	1.57	1.62	1.67	1.71	1.72	1.77	1.81	1.83	1.86	1.88	1.90	1.91	1.95	2.00	2.18
Wick	2.40	2.48	2.58	2.66	2.73	2.75	2.83	2.88	2.91	2.95	2.98	3.01	3.03	3.08	3.16	3.44
Moray Firth	2.87	2.94	3.04	3.14	3.25	3.30	3.43	3.51	3.57	3.67	3.74	3.80	3.85	4.00	4.20	5.19
Clachnaharry	3.17	3.26	3.40	3.51	3.63	3.68	3.82	3.91	3.99	4.09	4.18	4.24	4.30	4.46	4.71	5.71
Aberdeen	2.70	2.78	2.89	2.96	3.04	3.07	3.14	3.19	3.23	3.28	3.32	3.35	3.37	3.44	3.54	3.90
Grangemouth	3.95	4.06	4.20	4.33	4.48	4.55	4.76	4.87	4.96	5.08	5.18	5.25	5.33	5.56	5.86	7.27
Leith	3.39	3.47	3.58	3.67	3.76	3.79	3.89	3.94	3.98	4.04	4.09	4.12	4.16	4.24	4.38	4.94
North Shields	3.22	3.30	3.41	3.50	3.61	3.64	3.75	3.83	3.88	3.96	4.02	4.07	4.11	4.22	4.38	5.04
Whitby	3.38	3.48	3.61	3.72	3.85	3.89	4.04	4.14	4.21	4.31	4.39	4.46	4.51	4.66	4.89	5.79

Site	Return period (years)															
	1	2	5	10	20	25	50	75	100	150	200	250	300	500	1,000	10,000
Immingham	4.19	4.31	4.47	4.62	4.77	4.82	5.00	5.11	5.19	5.32	5.41	5.48	5.55	5.73	6.01	7.10
Cromer	3.15	3.29	3.50	3.67	3.84	3.90	4.13	4.27	4.37	4.53	4.63	4.72	4.79	5.00	5.30	6.65
Lowestoft	2.10	2.28	2.54	2.76	3.00	3.07	3.32	3.48	3.59	3.76	3.88	3.98	4.05	4.28	4.63	5.96
Felixstowe	2.73	2.87	3.07	3.25	3.44	3.51	3.73	3.88	3.98	4.13	4.24	4.33	4.40	4.64	4.98	6.35
Sheerness	3.77	3.86	3.99	4.13	4.28	4.33	4.54	4.66	4.74	4.88	4.98	5.07	5.14	5.34	5.64	6.92
Dover	3.88	3.98	4.11	4.22	4.36	4.40	4.54	4.63	4.69	4.78	4.85	4.90	4.95	5.07	5.25	5.94
Newhaven	3.88	3.96	4.08	4.18	4.29	4.33	4.45	4.53	4.59	4.68	4.75	4.81	4.86	5.01	5.24	6.13
Portsmouth	2.60	2.67	2.76	2.83	2.92	2.95	3.03	3.09	3.13	3.19	3.23	3.27	3.30	3.38	3.49	3.94
Bournemouth	1.42	1.50	1.60	1.69	1.79	1.82	1.93	2.01	2.06	2.14	2.19	2.24	2.28	2.38	2.54	3.17
Weymouth	1.84	1.91	2.02	2.11	2.20	2.24	2.34	2.39	2.43	2.50	2.55	2.59	2.62	2.71	2.84	3.44
Exmouth	2.78	2.87	3.00	3.11	3.22	3.26	3.37	3.44	3.49	3.57	3.62	3.66	3.69	3.79	3.93	4.50
Devonport	2.95	3.03	3.13	3.20	3.28	3.31	3.40	3.45	3.49	3.54	3.58	3.62	3.64	3.72	3.83	4.30
Belfast	2.21	2.30	2.43	2.56	2.70	2.74	2.90	3.01	3.08	3.19	3.26	3.33	3.38	3.53	3.76	4.70
Portrush	1.66	1.75	1.88	2.00	2.11	2.15	2.28	2.37	2.44	2.53	2.60	2.66	2.70	2.84	3.04	3.82

Notes: Levels are given in metres Ordnance Datum (mOD) unless stated and are correct to base year 2017. Sites marked with * are referenced to a local datum.

4.2. Model validation

The performance of the SSJPM approach was evaluated using various diagnostics including:

- comparison with observed sea levels
- estimates from models for annual maxima
- regional frequency analysis (RFA) approaches

Gauges were also validated using their annual maximum series, and whether events corresponding to certain return period estimates under the SSJPM occurred as often as expected. The validation process also included evaluating return period estimates from the model corresponding to historical events.

To compare against observed levels, return periods were estimated empirically from the set of high water levels from each tidal cycle, which were de-clustered so that independent events were analysed. Levels that were exceeded (for example, 5 times in a 20-year record) have an empirical return period of 4 years. This approach is not recommended as a means of estimating return levels, but can be a useful indicator of model fit. This analysis shows that, for most gauges, the SSJPM fits well to the data and produces a set of realistic and physically plausible levels at higher frequency extreme events.

Alternatively, comparisons can be made with estimates obtained from fitting a model to annual maximum water levels; this is typically represented as a GEV distribution. The SSJPM results were compared with those from the GEV model as a sense check. In the majority of cases, levels for the GEV and SSJPM agree for low return periods. However, the GEV model tends to underestimate high return periods, which is a consequence of large tidal variations relative to surge variations (Dixon and Tawn 1999). The SSJPM, in contrast, models the stochastic surge component of water levels and avoids the biases of the GEV approach.

The RFA approach required the fitting of threshold excess models to water levels in clusters of tide gauges, where each individual tide gauge is associated with a local index that is used to transform cluster return levels to gauge-specific return levels. The RFA estimates tend to agree with SSJPM estimates for low return periods. While the 2 methods compare reasonably well at high return periods, physically unrealistic return levels are obtained at some gauges due to the lack of constraint on the shape parameter. The SSJPM, in contrast, produces a set of stable and spatially consistent shape parameters that result in sensible levels at high return periods.

A full comparison of the SSJPM with empirical, GEV and RFA estimates of return levels are detailed in Appendices F and G.

Figures 4.1 and 4.2 show selected ESLs from the 2018 update compared with water levels from 2 widespread coastal flooding events in December 2013 and January 2014 respectively. Historical water levels are shown for affected portions of the coastlines where the events were the AMAX events of record.

These were significant widespread events affecting many gauge sites and so a spatial pattern in severity around the coastline would be expected. It is also expected that water levels at neighbouring gauge sites would have similar return period estimates and therefore fall consistently above or below particular ESLs.

The December 2013 event (Figure 4.1) in particular provides a good test of the return period levels as the event was rare. Hence the associated higher return period ESLs are less well represented in the recorded data and have greater uncertainty. Note that while event magnitudes should not be derived from still water levels alone, they are still useful as a relative measure of severity.

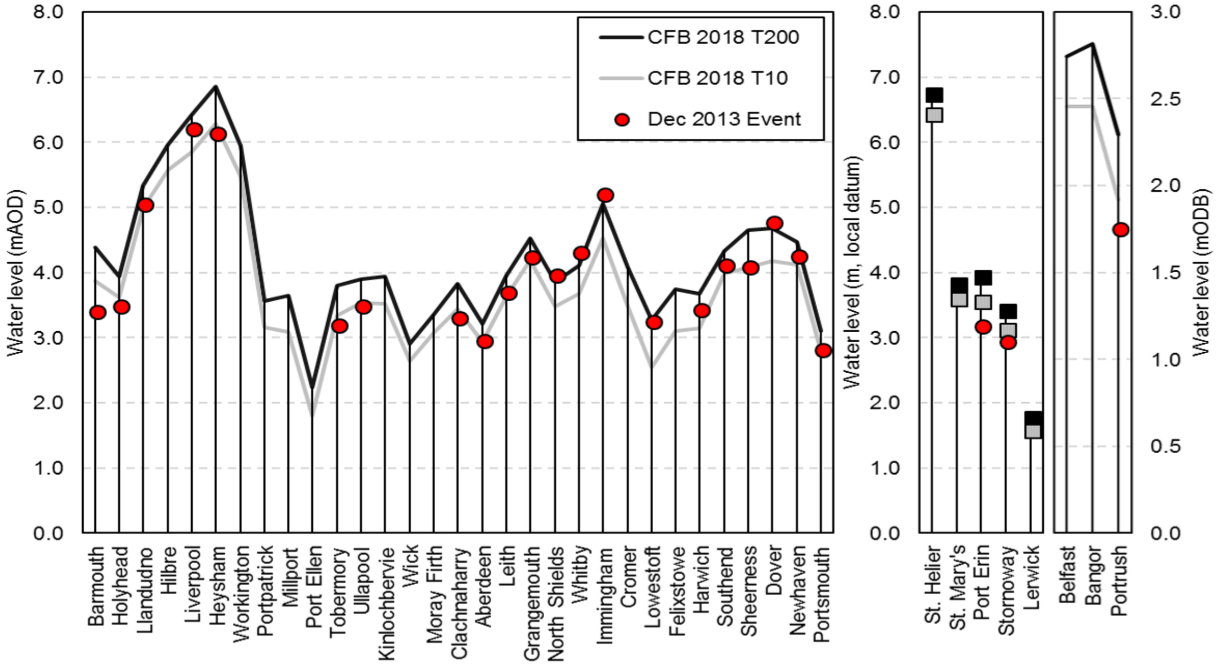

Figure 4.1: Historical water levels (corrected to 2017 base year) for the December 2013 event (red dots), along with the 2018 update ESLs for the 10 and 200-year return periods (light grey and black lines or squares)

Notes: Historical water levels are only shown where this event was the event of record in the gauge AMAX series. mAOD = metres above Ordnance Datum; mODB = metres Ordnance Datum Belfast

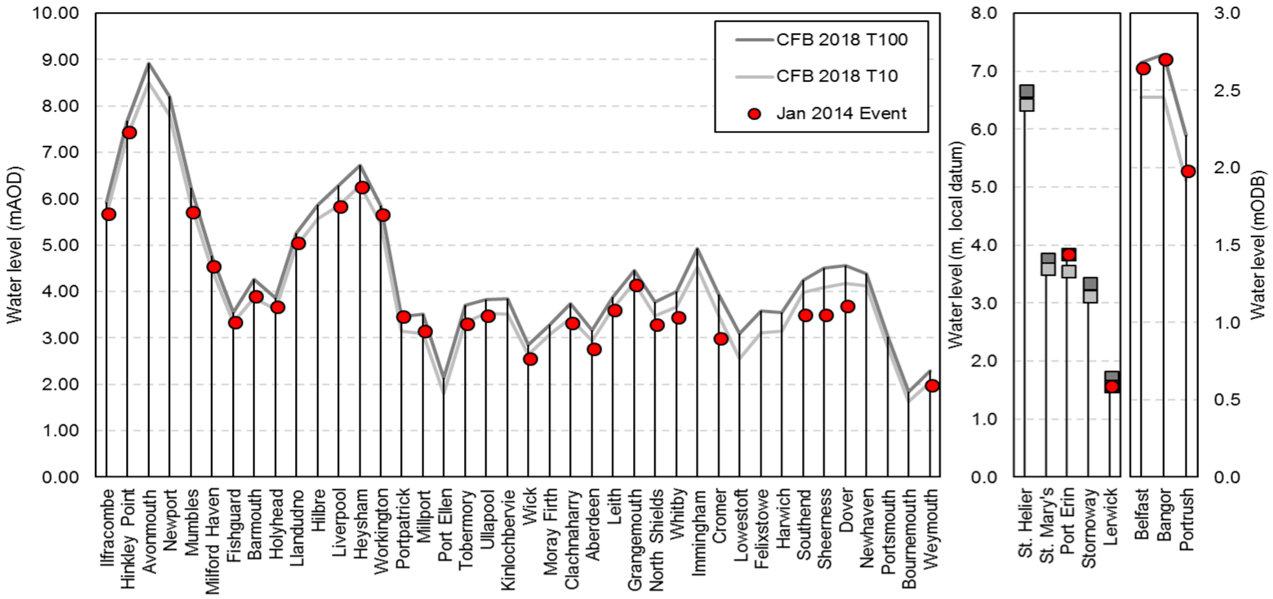

Figure 4.2: Historical water levels (corrected to 2017 base year) for the January 2014 event (red dots), along with the 2018 update ESLs for the 10 and 100-year return periods (light and dark grey lines)

Notes: Historical water levels are only shown where this event was the event of record in the gauge AMAX series. mAOD = metres above Ordnance Datum; mODB = metres Ordnance Datum Belfast

The all event comparisons generally show good agreement in return period estimates, generally following consistent patterns with neighbouring gauge sites. Exceptions include the following:

- Dover – the 2013 event is above the 200-year level while neighbouring sites are lower. This indicates that either this event was locally very severe for some physical reason or that the Dover return periods are underestimated.

- Sheerness – the 2013 event is well below the 200-year level in comparison with neighbouring gauges. This indicates that the levels are Sheerness may be overestimates.
- Mumbles – the 2014 event is generally less than 10-year at most neighbouring gauge sites, while Mumbles is above 10 years. This either indicates a locally severe event at Mumbles or that the Mumbles levels may be slightly underestimated.

For each of these events, the recorded sea levels are not quite consistent with the return period levels of neighbouring gauge sites, indicating that the levels may overestimated or underestimated. However, these inconsistencies may also be due to weather conditions for these events being unique to the site. Effects such as wave and wind set-up (see Section 1.5, Note 2) may have affected sea levels at these gauges for these effects.

Overall, the validation discussed in this section and Appendix G suggests that the CFB 2018 estimates of return levels are sensible. Overall user confidence in these levels was assessed by combining the findings of the GEV, RFA and empirical approaches, along with the uncertainty in the model estimates, and summarised using a metric. This metric identified some gauges where confidence is lower than others: Kinlochbervie, Liverpool, Newport, Padstow and Exmouth.

Despite this lower confidence, the SSJPM estimates are recommended as the best available information, though this lower confidence may be considered dependent on the user’s application of these levels. Other gauges that were identified as notably problematic discussed below along with recommendations for use.

4.2.1. Sheerness and Southend

The levels at Sheerness appear to be slightly overestimated. It is thought this may be due to difficulties in producing accurate tidal predictions at this site, as detailed in Hibbert et al. (2015). Predictions of peak tide also affect skew surge by definition and there appears to be a weak correlation between skew surge and peak tide at Sheerness, resulting in slight overestimation of return periods levels. Further work is required to investigate this. The size of this overestimation is unknown and so it is recommended that the median return levels (as at other sites) are used for flood risk analysis as a conservative estimate of level.

It is not recommended that the Southend levels are used in place of Sheerness. Data quality issues were found in the gauge record that resulted in half the number of skew surges being discarded. Many of these levels correspond with times of large skew surge events and so it is likely the return levels at this site would be underestimated.

4.2.2. Avonmouth and Portbury

The Portbury tide gauge was installed to replace the Avonmouth tide gauge, and so they are very close to each other. However, the levels at these sites are not comparable (see Section B.3 in Appendix B). This requires further investigation. Importantly, the Portbury levels fall within the Avonmouth confidence levels and so it is recommended that the Avonmouth levels are used in preference. The Avonmouth gauge has the longer record and thus smaller confidence intervals overall.

4.2.3. Felixstowe and Harwich

Similarly, Felixstowe and Harwich are located very close to each other and very similar levels are estimated at the 2 gauges. It is recommended that the Felixstowe levels are used in place of the Harwich levels due to the longer, more reliable data record at Felixstowe.

4.2.4. Lerwick

The SSJPM estimates appear to be underestimates by up to 0.1m in comparison with empirical estimates of recorded events at low return periods. The reason for this is unclear and requires further investigation. As the RFA approach has better agreement with observed sea levels, it is recommended that levels estimated using RFA should be used at Lerwick. This is the only gauge where RFA is recommended instead of SSJPM. The confidence intervals provided for Lerwick reflect the SSJPM confidence widths.

4.2.5. Bangor and Belfast

There is reasonable uncertainty in the Bangor estimates, while there are several data issues with the Belfast gauge, particularly in the period post-1990. It was decided to exclude this period as the resulting SSJPM estimates showed better agreement with observed water levels. It is recommended that the Belfast estimates are used in place of Bangor.

4.2.6.Grangemouth

Data quality at Grangemouth is variable resulting in only half the skew surge being disregarded from the analysis. The SSJPM return level estimates are also less well validated by empirical estimates. The SSJPM levels at Grangemouth have nevertheless been applied at the site as the best available information. Wind set-up is considered a possible contributor to extreme water levels at this location and not necessary included in existing models, which could have otherwise been used to derive levels at Grangemouth.

4.3. Standard surge shapes

Surge shapes are provided in a Microsoft® Excel spreadsheet (Design Surge Shapes.xls) for 43 UK NTGN sites around the UK. This spreadsheet accompanies the shapefile CFB_Surge_Shape_2018.shp,[3] which provides a reference for the surge shape to apply at the UK NTGN sites as well as for a respective section of the coastline.

Coverage is for the UK mainland coast together with the following islands:

- Isles of Scilly
- Isle of Man
- Isle of Arran
- Western Isles (including Islay, Jura, Coll, Tiree, Skye and Rum)
- Outer Hebrides
- Orkney Islands
- Shetland Islands
- Isle of Wight

The surge shapes to use and the geographical bounds to apply these surge shapes are given in Appendix I.

[3] Both are available on data.gov.uk.

5. Conclusions and recommendations

The ESLs presented in this report provide the first update to the original CFB study (Environment Agency 2011). The levels are to base year 2017; 2.5% and 97.5% confidence bounds are also provided.

Levels are output at the same 2km locations as for the 2011 CFB study. In addition to these, levels are provided for Northern Ireland, Jersey and at estuary, tidal river and sea loch locations, where levels were not previously provided but which were required for a range of coastal and fluvial studies.

Analysis to derive ESLs used significantly increased lengths of recorded levels at some gauge sites. In general, a further 10 years of data were available for analysis. Additional data were derived from analysis of secondary gauges at NTGN sites. Within the time period of the additional 10 years, several large sea level events have occurred, notably during the storm events of 2013 and 2014.

The addition of large sea level events and increases to the data record provides a test of the SSJPM and shows the return period levels estimated using this method to be relatively robust. Only small changes of less than 0.1m are observed at most gauge sites despite 2013 and 2014 seeing some of the largest events on record. The largest differences are observed in south-east England where the December 2013 data are likely to have had some influence on the statistical fitting of skew surge.

Larger changes in return levels are observed at other sites including Mumbles and Lerwick. These changes occur at both low and high return periods, and so are more likely to be due to improvements in methodology. The 2018 update applies improvements in:

- de-tiding
- de-trending
- extremal index estimation
- statistical estimation of the shape parameter
- derivation of confidence intervals

The effect of these new methods and the addition of data on confidence intervals is varied. In some locations, the confidence intervals are reduced while elsewhere the confidence intervals are increased. This is because the confidence intervals have taken account of a larger range of uncertainty factors, namely the uncertainty in the threshold used to fit the GPD and this is not always offset by the addition of data.

Overall, changes in return levels of up to 0.3m are present in the 2km return level dataset compared with the 2km levels from Environment Agency (2011) despite smaller changes of 0.1m at UK NTGN locations. This is due to improvements in the interpolation of CS3X modelled levels, which have been validated against predicted high tides.

Extensive validation was carried out to test the SSJPM return level estimates at UK NTGN sites. Overall, the best available data and improved methods are applied in the 2018 update; however, the validation showed that some sites remain uncertain or show a poorer performance with the SSJPM.

After some investigations, the following recommendations and conclusions are presented.

- Despite the addition of data, some gauge sites – such as Southend and Belfast – have data quality issues that affect the performance of the SSJPM. For this reason, Southend was omitted from the dataset and some data were omitted in the Belfast SSJPM analysis. Data quality checking and routines are therefore crucial to this analysis and some sites may never be suitable for inclusion in this study due to the lack of quality control. This includes many non-NTGN sites, which rarely have duplicate recording devices for cross-validation of levels.

- Some large differences in return levels observed between the 2011 CFB study and the 2018 update are primarily due to differences in interpolation using the CS3X model and high tide validation. This is particularly the case where return levels change quickly across short distances around the coastline. Good interpolation of UK NTGN gauge return levels depends on good performance of the CS3X model and other sources of level data to inform the interpolation. Further updates to the CFB levels would therefore benefit greatly from improved, well-validated, high resolution modelling around the coastline, particularly in areas where return levels change quickly across short distances. This should include both high resolution meteorological data and model cell size. The quality of this modelling would be dependent on good validation and therefore the availability of good quality gauge data. However, the coverage of such data is variable and so, without further improvements to data quality and coverage, it may still be difficult to assess improvements in complex regions such as the Scottish islands.
- The confidence levels presented in this report and the shapefile of 2km return levels[4] represent the uncertainty associated with the skew surge joint probability statistics only. Additional uncertainty exists due to accuracy of the CS3X model, 2km interpolation and tidal predictions. Quantifying this uncertainty is not straightforward, but could be reviewed as part of future updates to the CFB.
- The problem at Sheerness highlights a possible issue if tides are poorly predicted. It is often difficult to predict tides in estuary regions and this may be creating a correlation in skew surge and high tide, resulting in overestimation of levels at the gauge. Alternatively, this may be the result of very large tide-surge interaction at Sheerness. Further investigation is needed to resolve this issue. It would also be beneficial to determine the effects of tidal prediction errors on return levels to fully take account of uncertainty in levels.
- Many tide gauge sites have some incomplete data. This results in the removal of skew surge for the tide in which it occurs. This assumption may need to be revisited in future to determine whether some skew surge could be included. The assumption results in significant reductions in data at Southend, Belfast and Grangemouth. There may be concern that removing large quantities of data might lead to very extreme events being excluded from the analysis. However, as the levels have changed so little since the 2011 CFB study in a period that saw several extreme coastal floods, there is a degree of confidence that the methodology is robust to this feature.

[4] CFB_Extreme_Sea_Levels_2018.shp or CFB_Extreme_Sea_Levels_Estuary_2018.shp in estuaries

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- JBA Consulting (led by Jennifer Hornsby and Matthew Hird) – conceptual processes, modelling calibration and verification, gauge data, and surge profile analysis and reporting
- National Oceanography Centre (led by Kevin Horsburgh) – extreme sea level modelling and reporting
- Professor Jonathan Tawn, Lancaster University – advice on extreme sea level statistical analyses
- Ivan Haigh, University of Southampton – peer review
- Tom Howard, Met Office – peer review
- Alastair McMillian, Royal HaskoningDHV – peer review
- Dominic Hames, HR Wallingford – peer review
- Alan Forster, AECOM – peer review
- Darren Price, Mott McDonald – peer review

8. List of abbreviations

AEP	annual exceedance probability
AMAX	annual maximum discharge
BODC	British Oceanographic Data Centre
CFB	coastal flood boundary
Defra	Department for Environment, Food and Rural Affairs
DfINI	Department for Infrastructure Northern Ireland
ECMWF	European Centre for Medium-range Weather Forecasting
ESL	extreme sea level
GEBCO	General Bathymetric Chart of the Oceans
GEV	generalised extreme value
GIA	glacial isostatic adjustment
GPD	generalised Pareto distribution
HAT	highest astronomical tide
MHWS	mean high water spring tide
mOD	metres Ordnance Datum
NOC	National Oceanography Centre
NTGN	National Tide Gauge Network
ODN	Ordnance Datum Newlyn
RFA	regional frequency analysis
SEPA	Scottish Environment Protection Agency
SSJPM	skew surge joint probability method

Appendices

Appendix A: Study area maps

KEY:

CFB update 2018 levels

Gauge

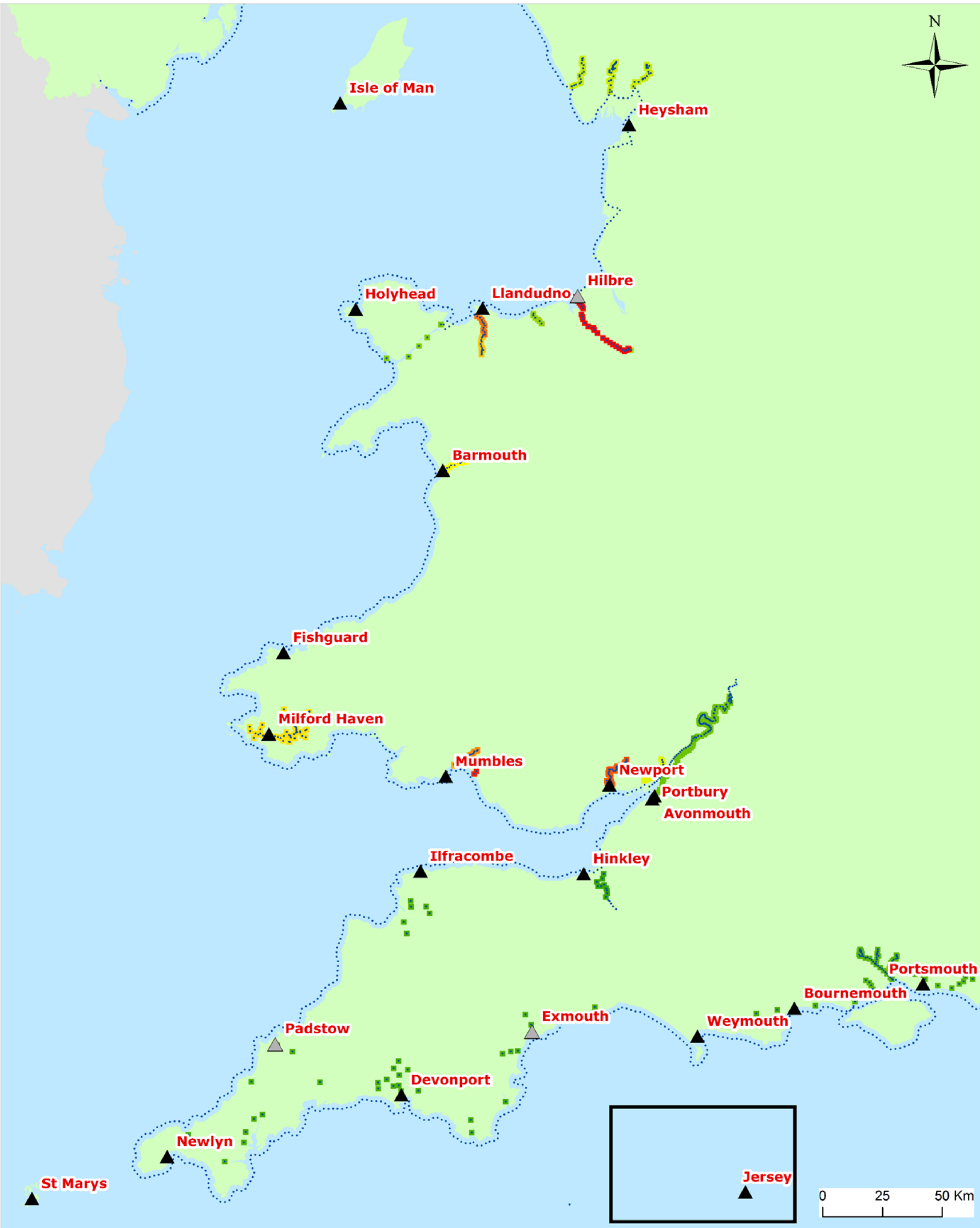
- NTGN
- Other

Estuary models

- 2006, Northern Area Tidal Modelling Overtopping
- 2008, Extreme Tide Levels in Estuaries and Tidal Rivers in South West Region
- 2011, Solent Downs Extreme Sea Levels and Confidence Intervals
- 2017, Boston Haven Pre-Barrier Tide Levels
- 2014, Anglian Coastal Modelling Package
- 2015, Anglian Coastal Modelling Package
- 2016, North Kent Coast Model Review and Update

Figure A-1:
Location of CFB 2018 update levels, estuary levels and models: South and east England

Scale @A3:
1:1,500,000



KEY:

- CFB update 2018 levels

Gauge

- NTGN
- Other

Estuary models

- 2014, River Parrett Tidal Modelling
- 2008, Extreme Tide Levels in Estuaries and Tidal Rivers in South West Region
- 2011, Solent Downs Extreme Sea Levels and Confidence Intervals
- 2007, River Severn (Tidal) Flood Risk Mapping
- 2011, North Wales Tidal Mapping Study
- 2011, Tidal Clywd Flood Mapping Update
- 2011, Tidal Dee Flood Mapping Update
- 2012, North West Tidals ABDs (Areas Benefitting from Defences) Revisited
- 2014, Caldicot and Wentlooge Coastal VDM
- 2014, Mawddach Estuary Flood Study
- 2015, Haverfordwest Hydraulic Modelling
- 2016, Afon Conwy Phase 3 Modelling Study
- 2016, Hafod-Morfa Copperworks Flood Consequence Assessment
- 2016, Neath - Phase 2 Modelling Report
- 2017, Afon Conwy Phase 3 Modelling Study
- 2017, Mill Parade Flood Consequence Assessment
- 2017, Point of Ayr to West Rhyl Tidal Flood Risk Project
- 2017, Port Talbot Harbourside PAR Project Report
- 2015, Tidal Dee Flood Mapping

Figure A-2:
Location of CFB 2018 update levels, estuary levels and models: Wales, Northwest and southwest England

Scale @A3:
1:1,600,000

Environment Agency
SEPA Scottish Environment Protection Agency
Department for Infrastructure An Roinn Bonneagair
National Oceanography Centre NATURAL ENVIRONMENT RESEARCH COUNCIL
JBA consulting
Cyfoeth Naturiol Cymru Natural Resources Wales

KEY:

- CFB update 2018 levels

Gauge

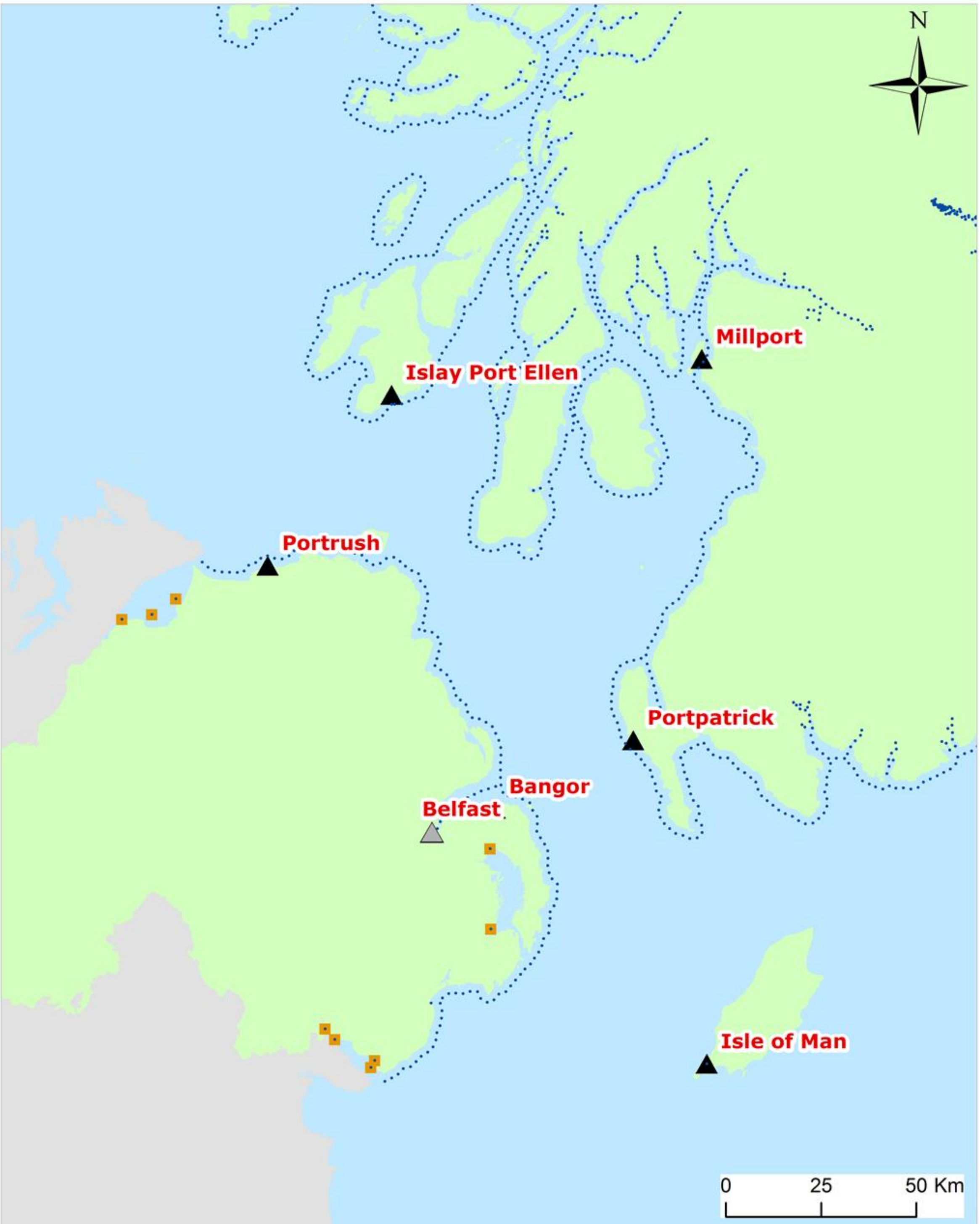
- ▲ NTGN
- △ Other

Estuary models

- 2018, Phase 1 SEPA Coastal Flood Mapping Update - Northeast Scotland and Orkney
- 2008, National Coastal Flood Hazard Mapping

Figure A-3:
Location of CFB 2018 update levels, estuary levels and models: Scotland and northern England

Scale @A3:
1:2,100,000



KEY:

CFB update 2018 levels

Gauge

Type

NTGN

Other

Estuary models

2008-2013, Tidal Boundary Condition Studies

Figure A-4:
Location of CFB 2018 update levels, estuary levels and models: Northern Ireland

Scale @A4:
1:1,500,000

Appendix B: Tide gauge data

B.1.NTGN data review

An important objective of the 2018 update was to extend the gauge data records beyond that used in the previous study. Longer data records capture a greater number of rare events and so reduce uncertainty in the statistical analysis of ESLs.

The original study (Environment Agency 2011) used gauge data from 40 of the NTGN sites with data covering 1915 to 2008. For the 2018 update, NTGN data were extended up to and including 2016, that is, an additional 8–9 years of data. The extension to record lengths also resulted in more NTGN gauges having sufficiently long records to allow ESL analysis to be performed, resulting in 3 additional NTGN gauges being included in the 2018 update at Portbury, Harwich and Moray Firth. UK NTGN gauges at Bangor, Portrush and St Helier were included due to extension of the study area to Northern Ireland and Jersey.

Table B.1 lists all the NTGN gauges used in the 2018 update, including their record length and its change compared with Environment Agency (2011).

Table B.1: NTGN tide gauges used in the 2018 update

Name	Years with data	Record length (years)	Record length 75% complete (years)	Increase over Environment Agency (2011) (%)	Number of cycles available	Cycles used (%)
St Helier (Jersey)	1992 to 2016	25	24	41.2	16,937	99.7
Newlyn	1915 to 2016	102	84	10.5	61,894	97.0
St Mary's (Isles of Scilly)	1968 to 1969, 1973, 1975 to 1978, 1987 to 1989, 1994 to 2015	32	21	50.0	17,022	97.7
Ilfracombe	1968 to 1971, 1977 to 1979, 1981 to 2000, 2002 to 2016	42	30	36.4	23,329	97.5
Hinkley Point	1990 to 2010, 2012 to 2016	26	24	26.3	17,285	95.6
Portbury	2008 to 2016	9	7	100	4,900	97.4
Avonmouth	1961 to 1976, 1979 to 1984, 1986 to 2012	40	25	13.6	20,004	98.6
Newport	1993 to 2016	24	23	64.3	16,038	96.5
Mumbles	1988 to 1993, 1997 to 2014	24	17	41.7	13,527	97.9
Milford Haven	1953 to 1962, 1964 to 1965, 1967 to 2016	56	37	27.6	31,579	97.0
Fishguard	1963 to 1971, 1973 to 2016	53	49	16.7	34,715	98.7
Barmouth	1991 to 2003, 2005 to 2016	25	21	50.0	15,411	94.5

Name	Years with data	Record length (years)	Record length 75% complete (years)	Increase over Environment Agency (2011) (%)	Number of cycles available	Cycles used (%)
Holyhead	1964 to 1973, 1977 to 1985, 1987 to 1991, 1995 to 2016	46	41	20.6	28,484	98.9
Llandudno	1971 to 2016	24	18	50.0	14,705	97.2
Liverpool Gladstone Dock	1990 to 2016	27	24	71.4	17,840	93.6
Port Erin (Isle of Man)	1992 to 1995, 1998 to 2016	23	21	50.0	15,006	99.3
Heysham	1964 to 1969, 1971 to 2016	52	41	17.1	31,730	97.6
Workington	1992 to 2016	25	25	47.1	17,215	99.3
Portpatrick	1968 to 2016	49	45	15.4	31,215	98.6
Millport	1978 to 1978, 1981 to 1983, 1985 to 2016	36	35	25.0	23,724	98.6
Port Ellen (Isle of Islay)	1979 to 1980, 1991 to 2011	23	19	5.6	24,102	99.8
Tobermory (Mull)	1990 to 2016	27	24	60.0	17,405	99.5
Ullapool	1966 to 1978, 1980 to 1983, 1985 to 2016	47	37	19.4	28,181	98.3
Stornoway (Hebrides)	1976 to 1976, 1978 to 1981, 1983, 1985 to 2016	38	35	25.0	24,081	98.9
Kinlochbervie	1991 to 2001, 2003 to 2016	25	23	53.3	16,577	99.6
Lerwick (Shetland Isles)	1959 to 2016	58	55	22.2	38,803	99.0
Wick	1965 to 2016	51	49	16.7	34,389	98.5
Moray Firth	1994 to 2004	11	6	20.0	5,969	97.3
Aberdeen	1930 to 1936, 1946 to 1953, 1955 to 1958, 1962, 1964 to 1965, 1967 to 1975, 1980 to 2016	68	52	20.9	36,468	98.0
Leith	1981 to 2016	29	25	38.9	18,485	99.4
North Shields	1946 to 1947, 1949 to 1956, 1961 to 1962, 1964 to 1975, 1978 to 2016	63	43	19.4	32,348	98.3
Whitby	1980 to 2016	37	31	19.2	22,969	98.2

Name	Years with data	Record length (years)	Record length 75% complete (years)	Increase over Environment Agency (2011) (%)	Number of cycles available	Cycles used (%)
Immingham	1953 to 1953, 1956 to 1958, 1963 to 2016	58	54	10.2	37,718	98.5
Cromer	1973 to 2016	32	28	40.0	19,604	98.1
Lowestoft	1964 to 2016	53	53	15.2	36,734	99.2
Felixstowe	1982 to 1982, 1984, 1986 to 2011	28	21	5.0	16,652	98.0
Harwich	1954 to 1960, 1967 to 1976, 2004 to 2016	30	26	44.4	19,124	98.8
Sheerness	1952 to 1952, 1958, 1965 to 1975, 1980 to 2016	50	45	21.6	32,036	99.1
Dover	1924 to 1924, 1926, 1928, 1930, 1934 to 1936, 1938, 1958 to 2016	67	58	16.0	43,003	98.8
Newhaven	1942 to 1948, 1950 to 1951, 1953 to 1957, 1964 to 1965, 1973, 1982 to 1988, 1991 to 2016	50	43	104.8	31,982	88.1
Portsmouth	1961 to 2016	56	50	177.8	37,578	95.2
Bournemouth	1996 to 2013	18	17	41.7	23,197	99.9
Weymouth	1967 to 1971, 1983 to 1987, 1989, 1991 to 2016	37	32	88.2	44,580	96.0
Devonport	1961 to 2016	56	50	194.1	35,918	90.9
Bangor	1994 to 2016	23	18	80.0	13,626	98.8
Portrush	1995 to 2016	22	21	50.0	14,955	99.6

As part of the 2018 update, a review of all NTGN data used in Environment Agency (2011) and that used in the extension to the end of 2016, was carried out. The aim of this review was to identify opportunities where data from supplementary instrumentation at each gauge location (referred to as the ALL dataset, see Table B.2) could be used to fill in gaps and maximise the data available for the ESL analysis.

The NTGN data used in Environment Agency (2011) originated from the processed (PRO) dataset produced by BODC. As explained in Table B.2, these data almost exclusively contain observations from the primary recording instrument (PRI, see Table B.3) at each tide gauge location. In some isolated periods at some gauges, the secondary recording instrument (SEC, see Table B.3) may have been used in the PRO dataset if the PRI instrument was not operational or was suffering severe or prolonged issues (for example, at Avonmouth for January to September 2002).

The review of the NTGN PRO data for gap filling compared the availability of observations from the ALL dataset (see Table B.2) during periods when observations in the PRO dataset were missing or marked as questionable quality.

Table B.2: NTGN tide gauge data types

<table>
<tr><th>Dataset abbreviation</th><th>Dataset description</th></tr>
<tr><td>PRO</td><td>Processed data that have passed through BODC quality control procedures
Data are released by BODC as annual files and include quality control flags for all observation times.
Data included in these files are:
- observed water level
- residual (observed water level minus astronomical tide level)
- data quality flag for each observation time
These data generally originate from the primary instrument at each location.
All observations are available at exact 15 minute sample intervals (that is, 0, 15, 30 and 45 minutes past the hour), or at exact 60 minute intervals (on the hour) for older data.</td></tr>
<tr><td>ALL</td><td>Data from all the recorders at each tide gauge location
Data have passed through BODC quality control procedures, but possibly not all checks used for the PRO dataset.
Data included in these files are observed water level from each complete tidal cycle instrument (primary and secondary) accompanied by a data quality flag for each observation time, for each instrument.
Multiple different types of instrument may be included in this dataset at a given tide gauge location. Types of instrument include bubbler gauges, Munro float gauges and pressure transducers.
Observations are available at their original recording time, that is, not necessarily at exact and consistent sampling intervals.</td></tr>
</table>

Table B.3: NTGN tide gauge recorders

<table>
<tr><th>Dataset abbreviation</th><th>Dataset description</th></tr>
<tr><td>PRI</td><td>The primary instrument at each tide gauge location
Data have passed through BODC quality control procedures.
These gauges record the water level for the complete tide cycle.
Since gauges record the lowest tidal levels, they can be prone to siltation in low tide conditions, which can impact the recording of water level until they are cleaned.
The instrumentation for the primary recorder may change over time.</td></tr>
<tr><td>SEC</td><td>The secondary or back-up instrument at each tide gauge location
Data have passed through BODC quality control procedures.
These gauges record the water level for the complete tide cycle.
Since gauges record the lowest tidal levels, they can be prone to siltation in low tide conditions, which can impact the recording of water level until they are cleaned.
The instrumentation for the secondary recorder may change over time.</td></tr>
</table>

Dataset abbreviation	Dataset description
MID	**A mid-tide or half-tide gauge now available at all NTGN locations** • These gauges only record the upper portion of the tidal cycle. • These gauges are very accurately levelled and are not prone to siltation as they do not read low water levels. • These gauges are used to verify the accuracy of the primary and secondary gauges during quality control procedures. • Data have passed through appropriate BODC quality control procedures. • Mid-tide gauges are now available at most NTGN locations (41 out of 46). • Mid-tide gauges have only been available at NTGN locations since 1993 at the earliest.

An example of the impact of the data infilling process on individual data series is shown in Figure B.1 for Dover for the calendar years 2014 to 2016. The merging of the PRO and ALL datasets resulted in a significant increase in data completeness for the years 2014 and 2015 compared with the PRO series by itself.

(a) PRO

(b) PRO + ALL

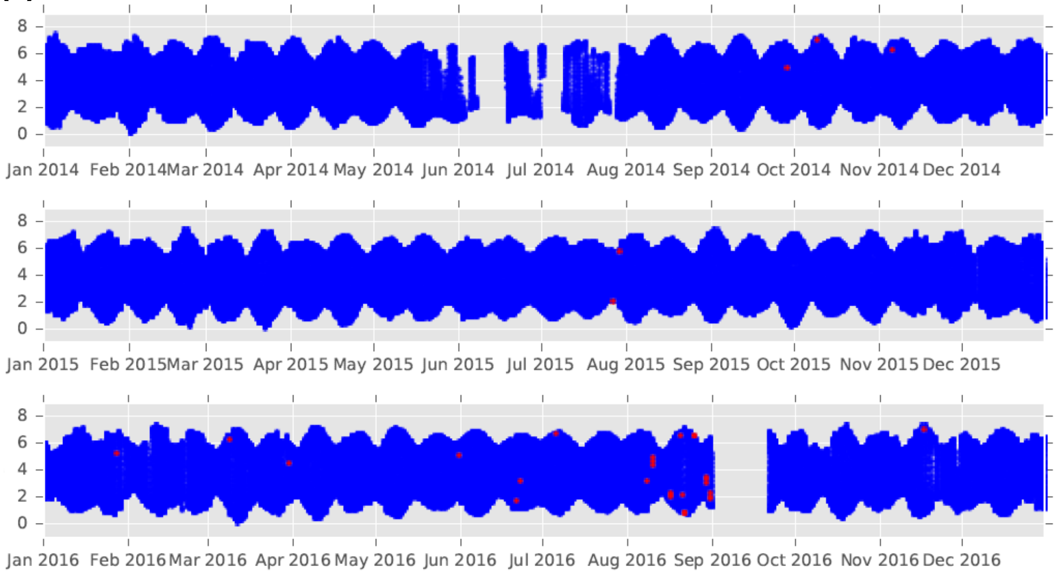


Figure B.1: Comparison of observed water level (m, relative to local Chart Datum) for (a) PRO and (b) PRO + ALL series for the calendar years 2014 to 2016 at Dover

Notes: Observations flagged as erroneous or flagged as interpolated values (that is, not directly observed) are shown in red. All other observations are shown in blue.

For both the Environment Agency (2011) and the 2018 update data periods, there was an overall increase in record lengths by supplementing data gaps in the PRO dataset with available data in the ALL dataset. However, there were gauges in both study periods for which the record length was not increased by this process. The majority of gauges saw very modest increases in record lengths through the data gap infilling process, but for a few gauges, the impact was large.

For the 2018 update, Devonport (25 years) and Portsmouth (26 years) yielded the greatest benefit from the data gap infilling process. Newhaven (15 years) and Weymouth (11 years) also benefited significantly.

As with the increases in record lengths, the data completeness at several gauges improved significantly as a result of the data gap infilling process. After infilling gaps in the PRO dataset, all NTGN gauges in the 2018 update had records that were at least 70% complete and 43% of the gauges (20 out of 46) had records that were at least than 90% complete. In the PRO dataset, the 90% complete threshold was exceeded at only 26% of gauges (12 out of 46) and the 75% complete threshold was met or exceeded by 83% of gauges (38 out of 46).

The 4 gauges with increases in data completeness greater than 25% for the 2018 update were the same 4 gauges with significantly increased record lengths: Portsmouth (51.4%), Devonport (46.4%), Newhaven (30.9%) and Weymouth (26.0%). The smallest increase in data completeness was at Port Ellen (0.006% increase), while Bournemouth, Felixstowe, Lowestoft, Millport, Newlyn, North Shields, Port Erin and Ullapool all showed minor (<1%) increases in data completeness.

In summary, the extension of NTGN tide gauge records to the end of 2016 and the inclusion of additional available data from supplementary instrumentation increased record lengths (for calendar years with at least 75%, or 9 months, of data available) by more than 5 years at 80% of gauges (37 out of 46) and by more than 10 years at 4 gauges.

B.1.1.Additional investigation: water level accuracy

In addition to infilling data gaps in the PRO records with data from the ALL dataset, the impact of relaxing the rigorous quality checking processes employed by BODC was also investigated.

The PRO dataset published by BODC is subject to strict quality checking to confirm it is suitable for a range of purposes, including those requiring high accuracy such as measuring long-term changes in sea level. ESL analysis, however, does not require the same high levels of accuracy as ESLs are generally only considered accurate to 0.1m. For ESL analysis, there is greater benefit from identifying the presence of extreme events in a record than from an accurate assessment of the exact sea level during the events. In addition, large events are also more likely to be associated with gauge failures or inaccuracies and so excluding large, slightly less accurate events may result in the ESLs being underestimated.

The relaxation of the strict quality control on water levels was achieved by comparing coincident water level observations in the PRO dataset flagged as questionable with those in the MID dataset (see Table B.3). Where coincident observations in both datasets differed by less than 0.05m, the questionable quality flag attached to the PRO observation was removed.

The investigation into the relaxation of water level accuracy was conducted for the PRO dataset extended to the end of 2016. This investigation identified that, for NTGN sites with the MID dataset available, the increase in overall data completeness was at most 5% (at Whitby). For most locations (33 out of 41 with MID data available), the improvement in data completeness was <2%.

The same investigation was conducted after the PRO gap filling procedure had been completed (that is, using the combined PRO and ALL datasets). The gap filling procedure had a major impact on the overall data completeness, filling gaps with questionable water levels in the PRO dataset with better quality data from the ALL dataset. Hence, the relaxation of water level accuracy applied to the combined dataset yielded only very small improvements in overall data completeness; only 6 locations (of the 41 with MID data available) showed an increase in data completeness >1% due to the relaxation in water level accuracy.

Following this investigation, it was decided not to implement the water level accuracy relaxation procedure for the NTGN dataset used in the ESL analysis.

B.2.Non-NTGN data review

In the earlier study (Environment Agency 2011), ESL analysis was only carried out at the 4 non-NTGN tide gauge sites (Padstow, Southend, Hilbre Island and Exmouth). However, 36 additional non-NTGN gauges were used for validation of ESLs interpolated along the coastline.

The 2018 update included a review of gauge data at several non-NTGN tide gauge locations for:

- their suitability for ESL analysis
- use in extending ESLs into estuaries, tidal rivers, lochs, loughs and harbours
- validation purposes only

Despite increases in data availability and record lengths, most non-NTGN tide gauge sites remained unsuitable for use in ESL analysis due to short record lengths and a lack of data quality controls. Unlike NTGN tide gauge sites, which operate several gauges at each site allowing for direct comparison of levels, non-NTGN tide gauge sites often only have a single gauge in operation. Single gauge sites were quality controlled using sensibility and datum checks, and by taking account of known operational problems at the gauge. Where possible, comparison with nearby gauges was also used to identify erroneous water levels that were not otherwise obvious.

B.2.1.Non-NTGN tide gauge data for ESL analysis

Six non-NTGN gauges were identified as having sufficiently long records and sufficient data quality for ESL analysis to be conducted using the SSJPM.

In addition, extensive investigations were conducted into the Exmouth gauge record and resulting ESLs, including a comparison with a highly accurate temporary gauge also located at Exmouth (Mason 2018). Based on these investigations, it was decided to use the Exmouth record as observed.

Details of these 7 gauges are given in Table B.4.

Table B.4: Non-NTGN tide gauges used in ESL analysis

Name	Years with data	Record length (years)	Record length 75% complete (years)	Number of cycles available	Cycles used (%)
Padstow	1998 to 2017	20	20	18,267	93.6
Hilbre Island	1964 to 1972, 1974 to 1975, 1977 to 1983, 1990 to 2003	32	22	16,158	92.9
Clachnaharry	1991 to 2017	27	26	19,210	99.9
Grangemouth	1999 to 2017	19	12	14,405	52.8
Southend	1994 to 2015	22	22	15,537	48.8
Exmouth	2000 to 2017	18	16	11,206	97.5
Belfast	1901 to 1902, 1904 to 1906, 1910 to 1918, 1920 to 1927, 1931 to 1932, 1936 to 2017	106	89	65,460	93.3

B.2.2. Non-NTGN tide gauge data for extending ESLs into estuaries, tidal rivers, lochs, loughs and harbours

Four non-NTGN gauges were identified as having sufficient data quality to be used to extend the ESLs into estuaries, tidal rivers, lochs, loughs and harbours (Table B.5). These sites were chosen where modelled level data were not available. However, this list is not exhaustive and other non-NTGN gauges may have sufficient data length and quality for this analysis.

Table B.5: Non-NTGN tide gauges ESL extension into estuaries, tidal rivers, lochs and harbours

Name	Country	Period of record used in analysis	ESL gauge used
Llanelli	Wales	2004 to 2017	Mumbles
Pontycob	Wales	2010 to 2017	Mumbles
Tintern	Wales	2000 to 2017	Newport
Victoria Lock	Northern Ireland	1997 to 2013, 2015, 2017 to 2018	Port Erin

B.3. Additional investigation: Merging nearby sites

The 2018 update also investigated the possibility of combining water level series for NTGN gauges with short records from nearby gauges to produce longer records. The NTGN gauges investigated for merging were:

- Felixstowe – with Harwich (complementary data)
- Avonmouth – with Portbury (short record replacement gauge)
- Sheerness – with Southend (complementary data)
- Liverpool – with Hilbre Island (complementary data)

The suitability of gauges for merging was investigated by considering only those periods with coincident observations and using only data not flagged as questionable in the PRO dataset.

To allow direct comparison of water levels for coincident observations, all data were corrected to a common datum (ODN). The differences in total and residual water levels between the 2 sites being compared were calculated and plotted for all coincident observations. These differences were also plotted relative to the data at each site to identify any bias in the differences between high and low tides.

B.3.1.Felixstowe and Harwich

The Harwich gauge replaced the Felixstowe gauge in January 2013 following the decommissioning of the Felixstowe gauge. PRO data were available for the Felixstowe gauge between 1982 and 2011, while the Harwich gauge, operational since 1954, had an extended period with no data available during the period 1976 to 2004.

The 2 gauges overlap for the period 2004 to 2011. The Felixstowe gauge was located at the seaward end of Felixstowe Pier, slightly north along the coast from the River Stour estuary. The Harwich gauge has been located since 2004 at the seaward end of Harwich Pier, in the mouth of the River Stour estuary.

The total and residual water level differences (calculated as Felixstowe minus Harwich) for 2005 and 2010 are shown in Figure B.2. These 2 years are shown as representative of the rest of the overlapping period at the 2 gauges.

The total water level differences are generally smaller than ±0.4m for most of the coincident series up to early September 2010. After this time, larger and primarily negative differences greater than ±0.5m occur sporadically. These large negative differences occur when Harwich observed higher water levels than Felixstowe, and the differences seem to be larger at high tide. The residual water level differences also changed throughout the period of overlap at the 2 gauges.

The water level differences between the 2 gauges were considered significant relative to ESL accuracies. Harwich and Felixstowe were therefore not combined and the gauges were treated separately in the ESL analysis.

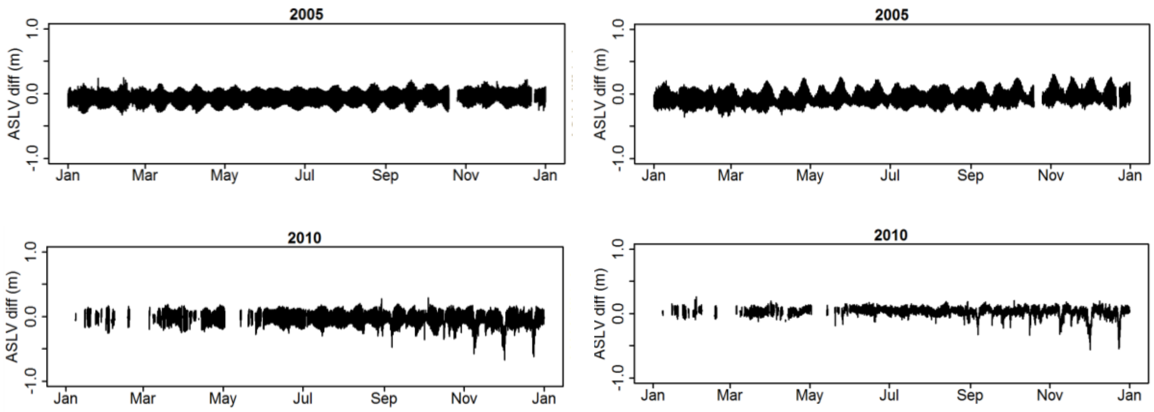


Figure B.2: Time series of Felixstowe minus Harwich differences for (left) total and (right) residual water levels for the years (top) 2005 and (bottom) 2010

Notes: ASLV = sea level http://vocab.nerc.ac.uk/collection/P02/current/ASLV/

B.3.2.Portbury and Avonmouth

The Portbury gauge replaced the Avonmouth gauge in April 2012 following the decommissioning of the Avonmouth gauge. PRO data were available for the Portbury gauge from 2009, while the Avonmouth gauge had been operational since 1961.

The 2 gauges overlap for the period 2008 to 2011. The Avonmouth gauge was located at the seaward end of the jetty just to the north of the mouth of the River Avon. The Portbury gauge is located on the pier near the inlet to the Royal Portbury Dock, on the south side of the mouth of the River Avon.

The total water level differences (calculated as Avonmouth minus Portbury) for all 4 years of overlap at the 2 gauges are shown in Figure B.3.

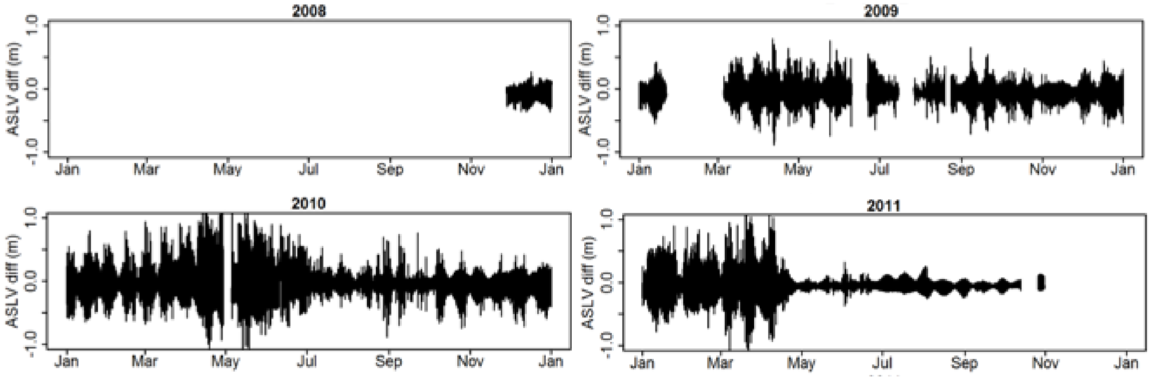


Figure B.3: Time series of Avonmouth minus Portbury differences for total water levels for the 4 years of overlap at the 2 gauges

Notes: ASLV = sea level http://vocab.nerc.ac.uk/collection/P02/current/ASLV/

The total water level differences exceed 1m on several occasions in early 2010 and 2011, but are smaller and less than ±0.5m at most other times. From late April 2011 onwards, the magnitude of the differences decreases drastically and the nature of the variability of the differences also changes. The smaller differences after April 2011 may indicate an attempt at calibrating the 2 gauges to provide a near continuous series, but BODC could find no record of this in site visit reports for 2011.

Data at Avonmouth and Portbury were included separately in the ESL analysis. The ESL results at the 2 gauges were compared to determine whether the possible errors in water level data produce large inconsistencies in ESLs between sites.

B.3.3.Sheerness and Liverpool

Following relaxation of the BODC flagging threshold and the infilling of flagged processed data with other channels, no supplementation of Sheerness data with Southend data or Liverpool with Hilbre Island data was deemed necessary. Both the Sheerness and Liverpool tide gauges had good record lengths and combining data would have introduced unnecessary errors into the dataset due to the different locations of the 2 gauges. Instead ESL analysis was carried out at all locations using separate data and the results were compared for validation.

B.4.Summary of data completeness

After determining the final dataset used for the ESL analysis, the quality of data completeness was assessed at each gauge every year. The data quality was determined to be:

- good if the record was at least 85% complete
- reasonable if the record was between 60 and 85% complete
- poor if the record was less than 60% complete

The results of this assessment are shown in Figure B.4.

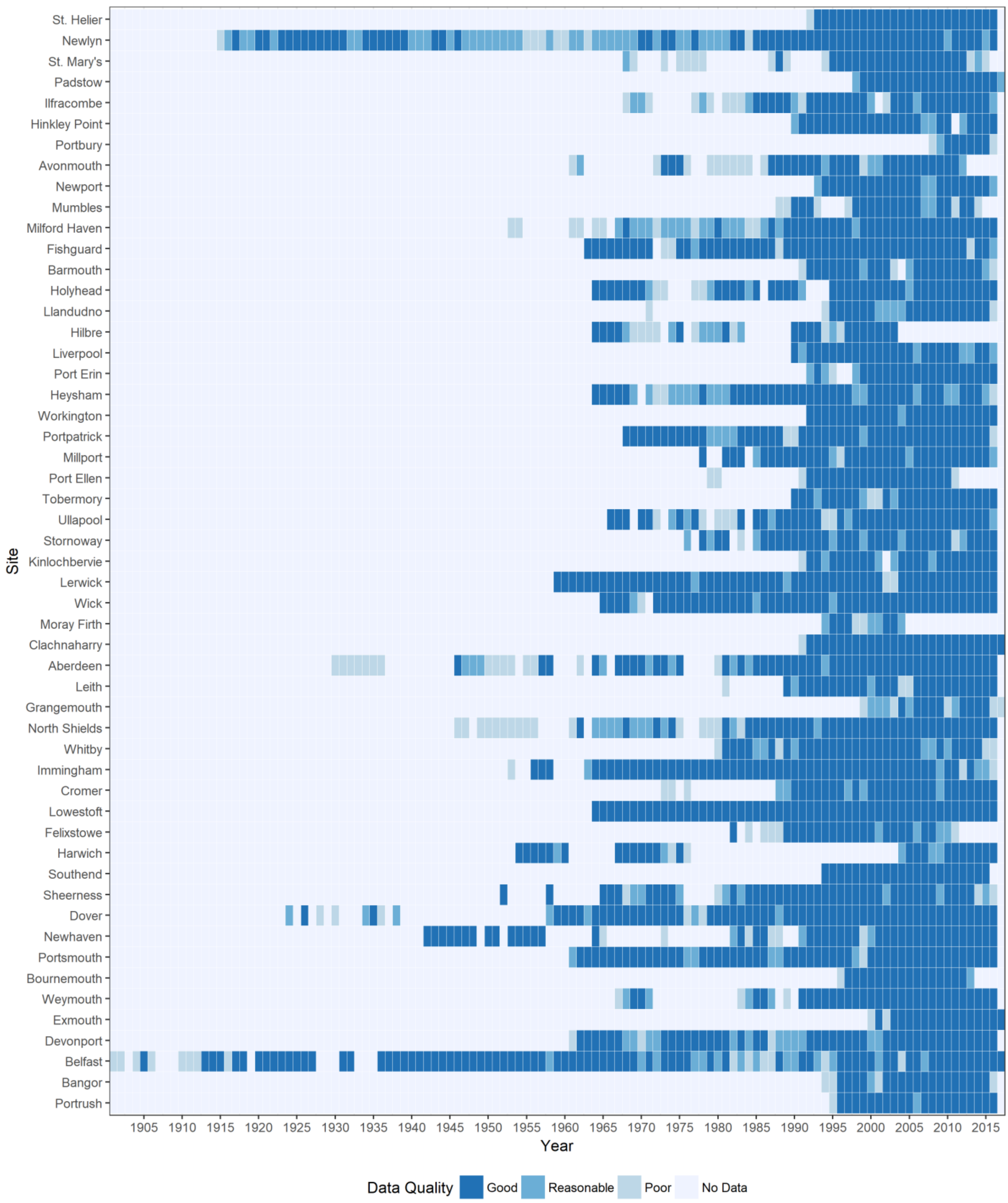


Figure B.4: Assessment of completeness of data used for ESL analysis grouped into good, reasonable and poor quality, and where no data are available

Appendix C: Coastal models

As in the original study (Environment Agency 2011), surge tide models were used to allow the ESLs calculated at tide gauges to be interpolated along the coastline between gauge locations. The models used in the 2018 update are identical to those used in Environment Agency (2011) and so the details of these models given in this appendix are reproduced from Environment Agency (2011), with some minor updates.

C.1.NOC CS3X continental shelf model

Numerical model hindcast simulations were used to:

- provide estimates of extreme water levels between tide gauge sites
- guarantee a consistent methodology around the entire coastline, including complex topographic regions

By using numerical models to interpolate dynamically, the correct spatial behaviour of the tide and storm surges in between tide gauge locations is represented. The NOC operational tide-surge model was used. This is at 12km resolution (CS3X) and forced by the ECMWF ERA40 meteorological re-analysis (at 1º resolution).

Numerical models tend to underestimate ESLs on average when forced by coarse resolution meteorological data. Nevertheless, they provide the correct dynamical response and can thus give return periods and levels at locations for which no observations exist when suitably calibrated with observational data.

Forcing the model surface boundary condition with long (40 year) meteorological re-analyses ensures that the modelled time series is comparable with the observational data and thus is statistically consistent. This was attempted by Flather et al. (1998), who used a depth-averaged tide-surge model of the European continental shelf with a horizontal grid of approximately 35km and forced it with the 40-year meteorological re-analysis provided by the Norwegian Meteorological Research Institute (Reistad and Iden 1995). They then compared the 50-year return period surge elevations with observational data and found reasonable agreement along the Dutch, German and Danish North Sea coastlines, though with a tendency for the model to underestimate the 50-year surge (by 0.3–0.5m) along the UK's North Sea coastline.

Previous modelling work was improved on significantly in this study by use of the 12km resolution operational surge model of the UK continental shelf (see Figure C.1) forced by the ERA40 dataset (Uppala et al. 2005). This re-analysis, provided by ECMWF, spans the period from 1960 to 2001 and has 6-hourly temporal resolution and 1° spatial resolution. The atmospheric forcing is linearly interpolated in time and space onto the surge model time-step and grid.

The CS3X storm surge model is a depth-averaged, shallow water hydrodynamic model based on discretisations originally described by Flather (1976). NOC numerical models used for surge prediction have been run operationally at the Met Office since 1978. The tide-surge model suite is subject to continuous upgrade and improvement, as described by Flather and Williams (2004). The present model covers the entire north-west European continental shelf with a regular grid of 1/9° in latitude and 1/6° in longitude. Surface boundary conditions to the surge model are the 10m wind and sea level pressure forecasts at hourly intervals. Tidal input is supplied at the lateral open boundaries of the model to support tide-surge interaction (see, for example, Horsburgh and Wilson 2007). Tidal input at the model open boundaries consists of the largest 26 constituents.

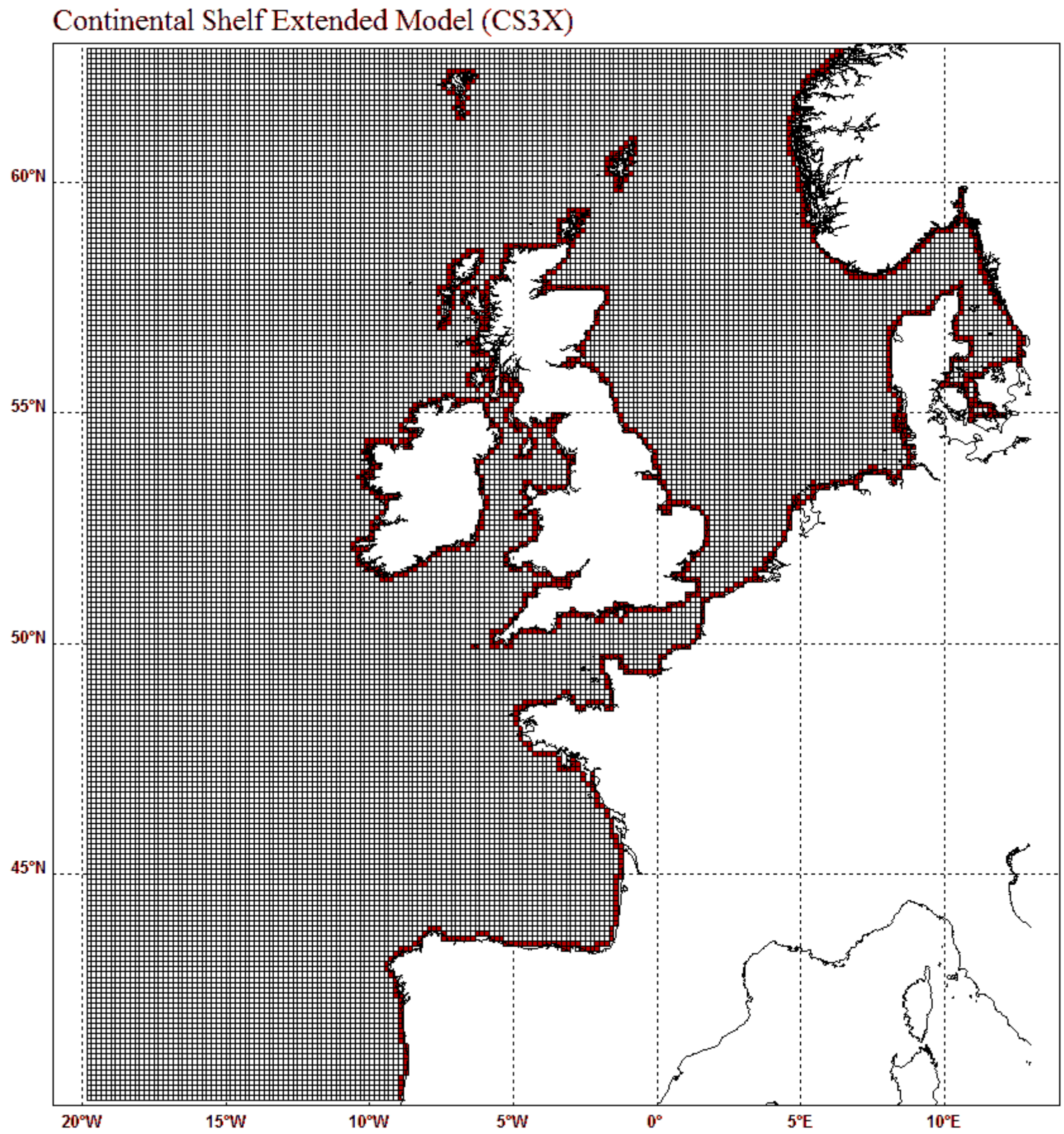


Figure C.1: NOC CS3X shelf wide tide-surge model domain

C.2.JBA North-east Irish Sea model

A separate, higher resolution model was used to produce results for the area within and adjoining Morecambe Bay. This area is characterised by areas of tidal flats that dry out at high tide.

The higher resolution model was used to represent the localised wetting and drying processes more accurately than NOC's larger 12km resolution model. This model, run by JBA Consulting, is a 2-D depth-averaged version of the Princeton Ocean Model (Blumberg and Mellor 1987). Like the NOC model, it is driven by ERA40 surface meteorology fields of air pressure and wind stress on a 1° grid at 6-hourly temporal resolution.

The model was run twice for the period of the ERA40 data to produce a hindcast data set of tidal levels and a dataset of total sea levels (including both tidal and meteorological forcing). These 2 datasets allow for the computation of the skew surge parameter, required for the SSJPM calculations at specific grid point locations.

The model domain encompasses 4.66°W to 2.5°W, 53.15°N to 55.15°N and performs calculations on a grid that has a variable resolution of approximately 1,000m in the west, increasing to 200m at the coastline. It is forced at the ocean boundary by the tide and surge components from a coarser resolution Princeton Ocean Model configuration of the continental shelf that is of equivalent design to the NOC model described above.

Bathymetry within the high resolution model domain was enhanced using cross-section sonar data from Morecambe Bay supplied by Lancaster City Council and LiDAR data provided by the Environment Agency for intertidal areas.

Appendix D: Estuary and harbour models

Modelled levels were interpolated to derive ESLs in upstream tidal locations. Details of the models used are given in Table D.1. Further details on these models are contained within each project's report and may be obtained from the modelling teams of the relevant operating authority.

Table D.1: Models of estuaries, tidal rivers, lochs, loughs and harbours used to extend ESLs into these areas

Name of modelled area	Base year	Region	Project/report title
Witham Haven	2017	England	Boston Haven Pre-Barrier Tide Levels
River Welland	2008	England	Northern Area Tidal Modelling Overtopping
River Parrett	2014	England	River Parrett Tidal Modelling
The Broads	2015	England	Anglian Coastal Modelling Package
River Medway	2016	England	North Kent Coast Model Review and Update
River Great Ouse	2014	England	Anglian Coastal Modelling Package
Duddon Sands	2012	England	North West Tidals ABDs Revisited
River Kent	2012	England	North West Tidals ABDs Revisited
River Leven	2012	England	North West Tidals ABDs Revisited
Clwyd	2011	Wales	Tidal Clywd Flood Mapping Update
Clwyd	2017	Wales	Point of Ayr to West Rhyl Tidal Flood Risk Project
Dee	2011	Wales/England	Tidal Dee Flood Mapping
Dee	2015	Wales/England	Tidal Dee Flood Mapping Update
Afan	2017	Wales	Port Talbot Harbourside project appraisal report
Mawddach	2014	Wales	Mawddach Estuary Flood Study, July 2016
Cleddau	2015	Wales	Haverfordwest Hydraulic Modelling
Neath	2015	Wales	Neath – Phase 2 Modelling Report
Menai Strait	2011	Wales	North Wales Tidal Mapping Study
Conwy	2017	Wales	Afon Conwy Phase 3 Modelling Study
Tawe	2016	Wales	Hafod-Morfa Copperworks Flood Consequence Assessment
Usk	2017	Wales	Mill Parade Flood Consequence Assessment
Severn	2007	Wales/England	River Severn (Tidal) Flood Risk Mapping
Severn	2014	Wales	Caldicot and Wentlooge Coastal Velocity Depth Mapping
Southwest	2008	England	Extreme Tide Levels in Estuaries and Tidal Rivers in South West Region

Name of modelled area	Base year	Region	Project/report title
Solent Downs	2011	England	Solent Downs Extreme Sea Levels and Confidence Intervals
Scotland	2008	Scotland	National Coastal Flood Hazard Mapping – based on various studies
Cromarty Firth	2018	Scotland	Phase 1 of SEPA's Coastal Flood Mapping Update – Northeast Scotland and Orkney
Northern Ireland	2008 to 2013	Northern Ireland	Strangford and Belfast Lough Extreme Tides Boundary Conditions Newcastle, Newry and Cranfield Extreme Tides Boundary Conditions Lough Foyle – Tidal Boundaries Belfast Lough Extreme Tides

Notes: ABD = areas benefitting from defences

Appendix E: SSJPM methodology

E.1.Joint probability analysis

A probability distribution of sea levels can be formed by decomposing the levels into their surge and tidal components, each of which has its own probability distribution. The skew surge distribution is modelled using a GPD, while the distribution of peak tides is derived from tide levels from the nodal cycle.

The probability of total water level is the geometric mean of the probabilities of all combinations of the possible skew surges with peak tide levels that sum to that total water level.

Critical to the joint probability approach is the assumption that skew surge and peak tide levels are independent, which empirical evidence suggests is a reasonable assumption to make.

E.2.Improved tidal analysis and prediction

For each tide gauge, a suite of programs to perform the tidal analysis, tidal prediction and estimation of the peak tides over a single 18.6-year nodal cycle were used. The new code used in this work is a fast MATLAB implementation of the industry-standard tidal analysis code developed at NOC (and previously the Proudman Oceanographic Laboratory). The code was written such that the astronomical arguments and nodal amplitude factors and phases are estimated continuously, leading to a more accurate analysis. Tidal constituents were estimated from the complete dataset at every tide gauge and from that the predicted tides were calculated along with the peak tides over a single 18.6-year nodal cycle.

In Environment Agency (2011), the datasets were analysed yearly and a new set of constituents produced for the tide gauge at various times leading to an inconsistent set of predictions at that site. In addition, peak tides were calculated previously using a separate software package, potentially introducing further inconsistencies. In this new analysis, all tidal information is calculated from the same suite of programs and tidal constituents, avoiding any biasing.

E.3.Mean sea level trend estimation

Before estimating the return levels at each tide gauge, the linear trend is removed from the dataset at each tide gauge. Although some studies suggest an acceleration in trend in recent years for very long records, these are still not statistically significant. Implementation of a time-varying trend would only increase the number of degrees of freedom in the system (and uncertainty), and would require significant research. Instead, relative linear trends were derived from the monthly records and vertical land movements – from a combination of global navigation satellite system (GNSS) measurements and glacial isostatic adjustment (GIA) models. In Environment Agency (2011), the linear trend was calculated for each tide gauge site from the available hourly data.

It is widely accepted that over 30 years of monthly or annual measurements is needed to derive a reliable linear trend from a tide gauge. Many of the UK sites would therefore fail this criterion and a bias in the skew surge results could be introduced. In this study, a set of trends was estimated from a new analysis by the NOC sea level group as the best estimate of the linear trend for each tide gauge. This approach uses a combination of tide gauge data, GPS derived estimates of vertical land movement, late Holocene derived sea level estimates, and models for GIA to derive a consistent set of trends for the UK. This constrains any outlying tide gauge results to spatially consistent values. To assess the uncertainty in the trends and its effect on the results, the final solution was run 3 times – once with the best fit trend and twice more with the trend plus 1mm per year and the trend minus 1mm per year. The final trends determined for each gauge are shown in Table E.1.

Table E.1: Trends applied to NTGN and secondary gauge records to correct for changes in mean sea level

Tide gauge	Trend (mm per year)		Tide gauge	Trend (mm per year)
St Helier	2.07		**Lerwick**	0.36
Newlyn	1.73		**Wick**	1.06
St Mary's	2.24		**Moray Firth**	0.49
Padstow	2.29		**Clachnaharry**	0.47
Ilfracombe	2.35		**Aberdeen**	1.02
Hinkley Point	2.71		**Leith**	0.79
Portbury	2.09		**Grangemouth**	0.48
Avonmouth	2.15		**North Shields**	1.69
Newport	2.94		**Whitby**	2.88
Mumbles	1.93		**Immingham**	1.43
Milford Haven	3.14		**Cromer**	1.91
Fishguard	1.76		**Lowestoft**	2.27
Barmouth	2.42		**Felixstowe**	1.71
Holyhead	1.82		**Harwich**	1.89
Llandudno	1.47		**Southend**	2.01
Hilbre	1.61		**Sheerness**	1.81
Liverpool	1.83		**Dover**	2.03
Port Erin	1.15		**Newhaven**	2.20
Heysham	1.52		**Portsmouth**	2.03
Workington	0.23		**Bournemouth**	2.07
Portpatrick	1.43		**Weymouth**	1.11
Millport	0.73		**Exmouth**	2.21
Port Ellen	2.35		**Devonport**	1.98
Tobermory	1.12		**Belfast**	0.92
Ullapool	1.19		**Bangor**	1.35
Stornoway	1.81		**Portrush**	0.70
Kinlochbervie	1.48			

E.4.Improved threshold selection and estimation of the shape parameter in the GPD

Skew surge values were derived by subtracting the predicted high water from that observed in each tidal cycle, which produces 705 skew surge values for a non-leap year. As with Environment Agency (2011), a statistical model was used to fit a smooth upper tail to the probability density function of the skew surges. The statistical model used is the GPD. The parameters in the GPD were set to give the best smoothed fit to the extreme skew surges above a specific threshold level.

The choice of threshold above which the GPD parameters are estimated can significantly alter the derived distribution. In Environment Agency (2011), the 97.5% quantile was chosen based on exploratory analysis. In this work, a more systematic exploration of the impact on overall uncertainty was adopted by testing 14 different threshold levels from 90% to 99% quantiles (every 1% up to 95% and then every 0.5% to 99%). The results were analysed to find the minimum threshold where the derived GPD shape parameter lay within the uncertainty bounds of all estimated shape parameters for higher threshold values. No single choice of threshold emerged from this investigation and so it was concluded that all thresholds are equally valid. Return levels were derived from all these different thresholds, as well as the 3 different trends in mean sea level. The return level was expressed as the median value for each return period.

In Environment Agency (2011), a smoothing procedure was applied to the derived shape parameter of the GPD at sites with return level estimates that appeared implausible (resulting largely from short data lengths or very high tides); the shape parameter at the site was averaged with that from 4 neighbouring sites. A limitation with this approach is that neighbouring sites could have equally implausible return levels.

A different approach was taken for the 2018 update. Instead of smoothing, the estimate of the shape parameter was constrained based on the spread and the mean of the full (unconstrained) estimates from all tide gauges. This ensured that the shape parameter remained closer to the group mean and would lead to a more consistent set of results, as there is no physical expectation for a spatial variation in the shape parameter. These constrained estimations were then applied to every tide gauge rather than just a subset that exhibited implausible return levels. The GPD shape parameter for all tide gauges is shown in Figure E.1. The shape parameter values used to generate the final ESL probabilities and return levels are shown by the black line.

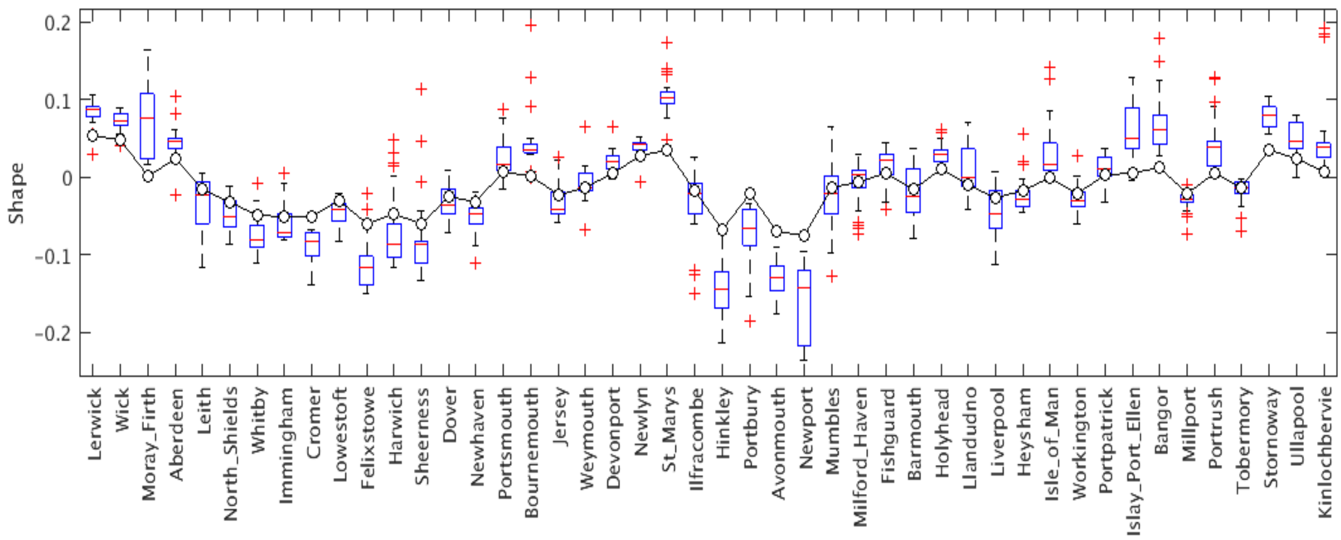


Figure E.1: Estimated shape parameter for the UK tide gauges.

Notes: Box plots highlight the range of the unconstrained estimates of the shape parameter for the 14 different percentile thresholds used, with red horizontal lines denoting the median of the unconstrained estimates and red pluses representing outliers. The black line with the circles is the median of the constrained solution.

E.5.Extremal index

Mid-latitude storms, which cause storm surges for the UK, have time and length scales that often span multiple tidal cycles. This can result in the clustering of ESL events (for example, large storm surges over successive tidal cycles) which are not statistically independent. If this clustering is not accounted for, the return periods for ESLs could be estimated to be more frequent than is actually the case, leading to an overestimation of a sea level for a particular return period.

The dependence is modelled using an extremal index (see, for example, Tawn 1992). Environment Agency (2011) used an extremal index as a function of sea level, estimated empirically as a mean cluster length over a particular tide gauge record. The approach taken examined the individual exceedance records in more detail. In simple terms, for each threshold, the number of exceedances was compared (as a ratio) to the number of exceedances over subsequent tidal cycles where sea level was below that threshold. The number of clusters and number of exceedances were used to calculate the extremal index.

In this update, further exploration was carried out into the minimum threshold above which the extremal index function is estimated. It was shown that setting this threshold to 95% of HAT is a sensible choice, as it produced functions indicating that tidal clustering reduces as the return period increases, as one might expect. Where extremal indices were required for levels below 95% HAT, the extremal index at 95% HAT was used.

E.6.Return level confidence interval estimation

The return level confidence intervals were estimated in the same manner as in Environment Agency (2011) but with one additional step. In Environment Agency (2011), bootstrap samples were derived from the fitted GPD, after which the GPD was re-fitted to each sample. This resulted in a distribution of return levels for each return period. Confidence intervals were obtained by extracting the necessary percentiles from this distribution.

Since a single fixed threshold level for estimating the GPD parameters (and therefore eventually the return levels) was not used in this study, the additional uncertainty had to be incorporated into the confidence intervals. To do this, the threshold percentile was found whose return levels most closely matched the median (but ignoring the uncertainty over mean sea level trends, which was found to have no significant effect). Alternative GPD tails were then generated at random, based on the tail from the chosen percentile. The GPD parameters (and return levels) were re-estimated at all percentile choices. This was done a total of 50 times, generating 700 return levels from which to estimate the confidence levels. This was tested against the method used in Environment Agency (2011). Although the confidence level increased slightly in most cases, it was generally within a few percent of the previous method.

Appendix F: Comparison of SSJPM return levels with observed levels and estimates derived from other approaches

This appendix compares the ESLs estimated from the SSJPM, de-trended to base year 2017, with observed levels and estimates from the AMAX GEV and RFA approaches. This comparison is done for all tide gauges.

Figures F.1 to F.53 present the comparisons for the 53 tide gauge sites in turn. In the plots:

- red lines represent estimates from the SSJPM in the 2018 study
- brown lines represent the levels from Environment Agency (2011) (where available)
- black lines represent estimates from a GEV model for annual maxima
- yellow lines represent estimates from an RFA
- blue dots represent the observed levels

The 90% and 95% confidence intervals (CIs) for the SSJPM estimates are shown by pink and purple dotted lines respectively.

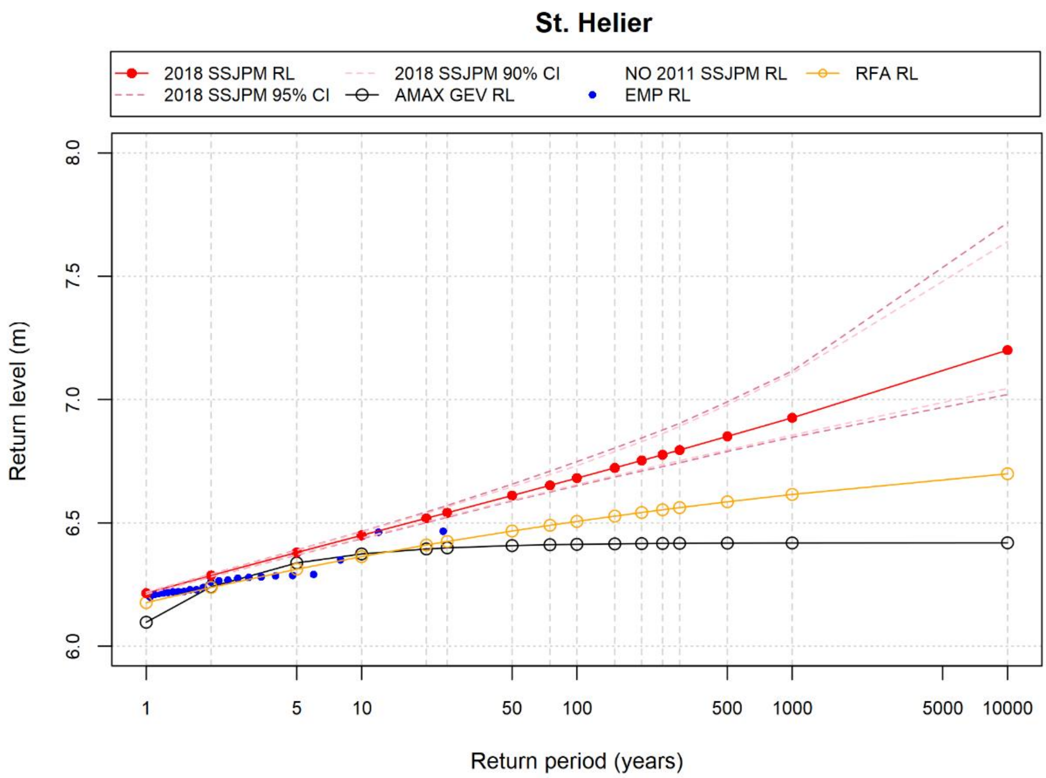


Figure F.1: Comparison at St Helier (Jersey) tide gauge site

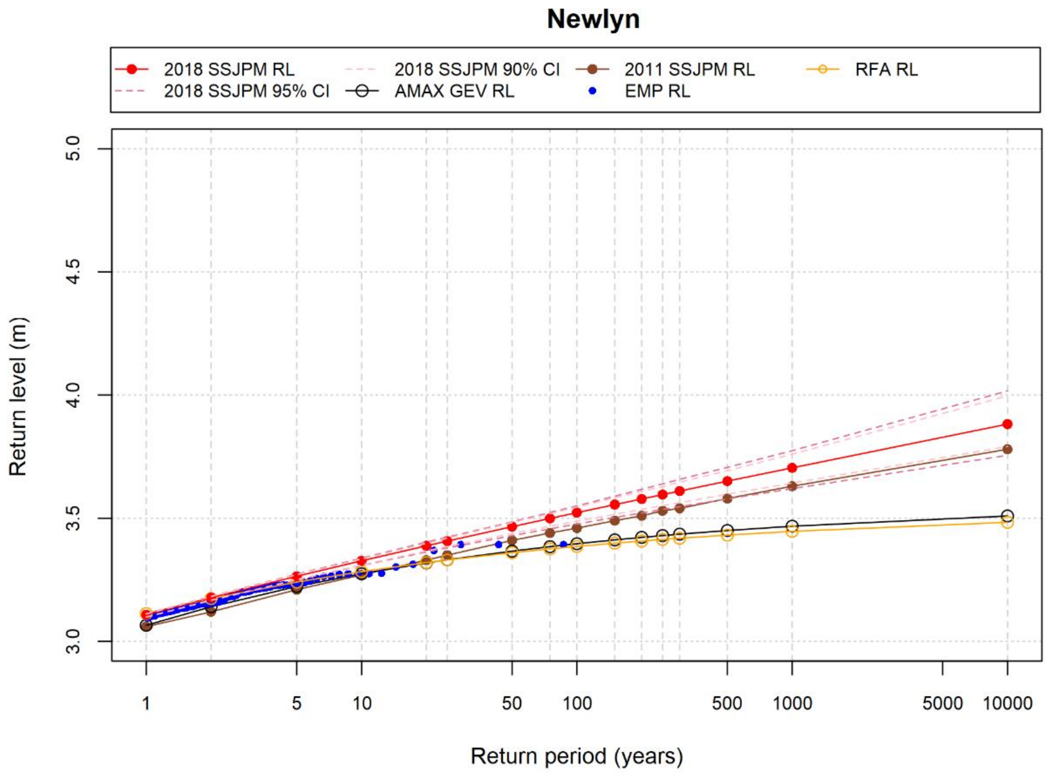


Figure F.2: Comparison at Newlyn tide gauge site

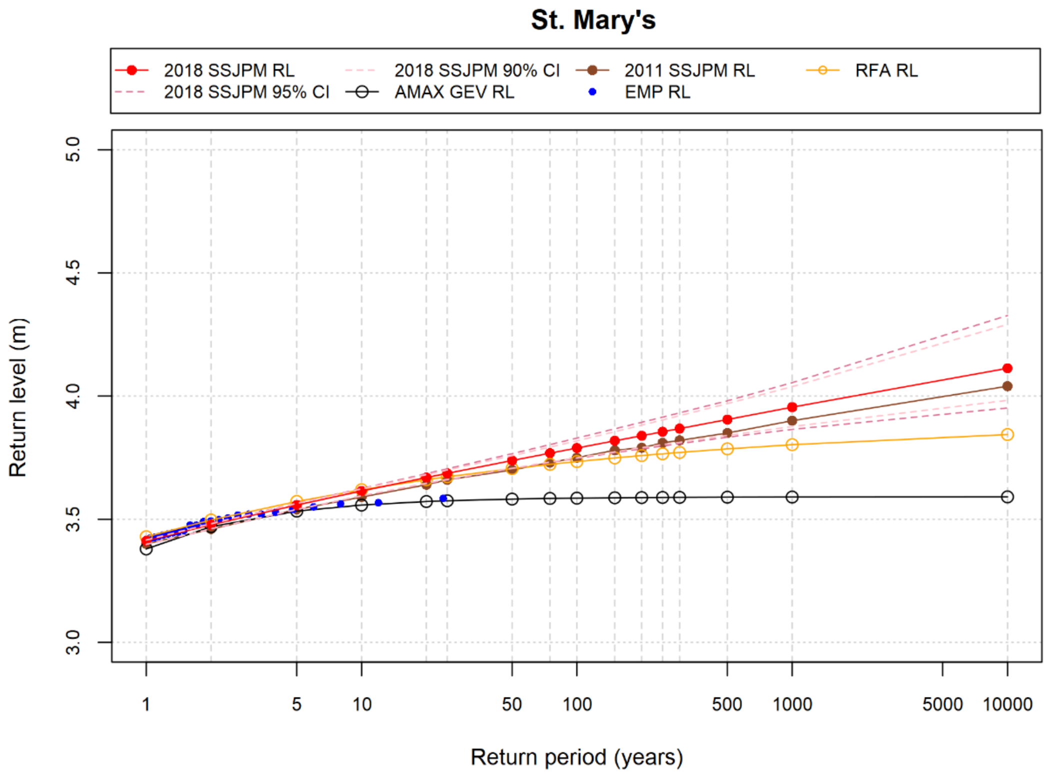


Figure F.3: Comparison at St Mary's (Isles of Scilly) tide gauge site

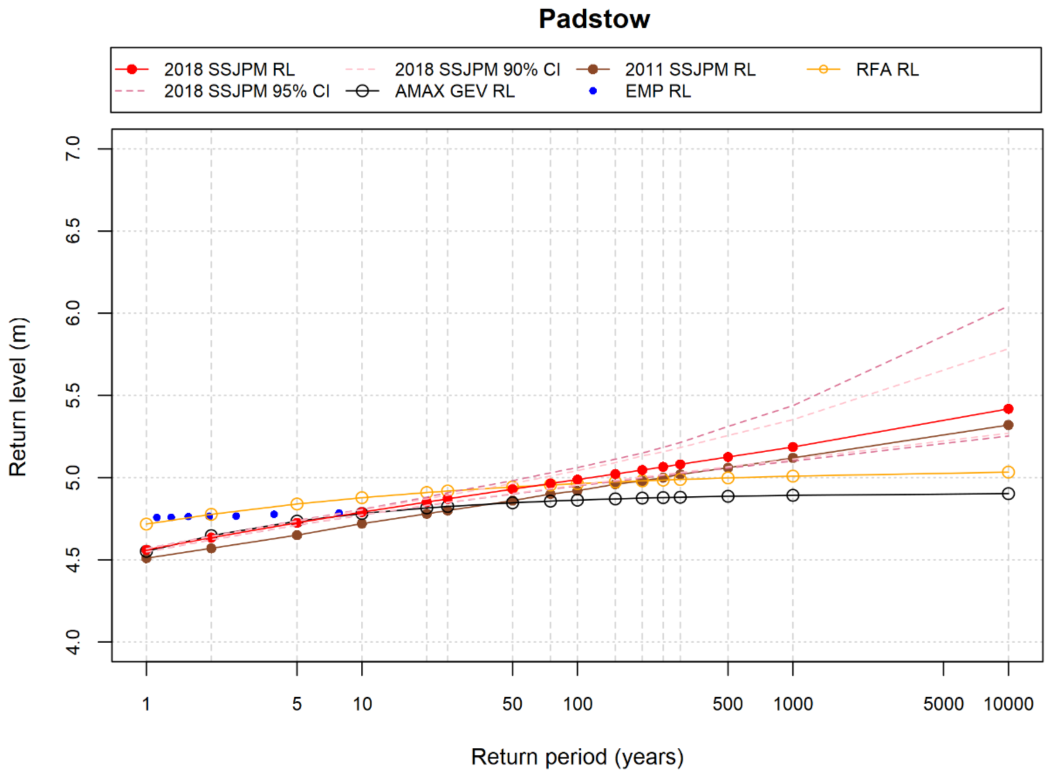


Figure F.4: Comparison at Padstow tide gauge site

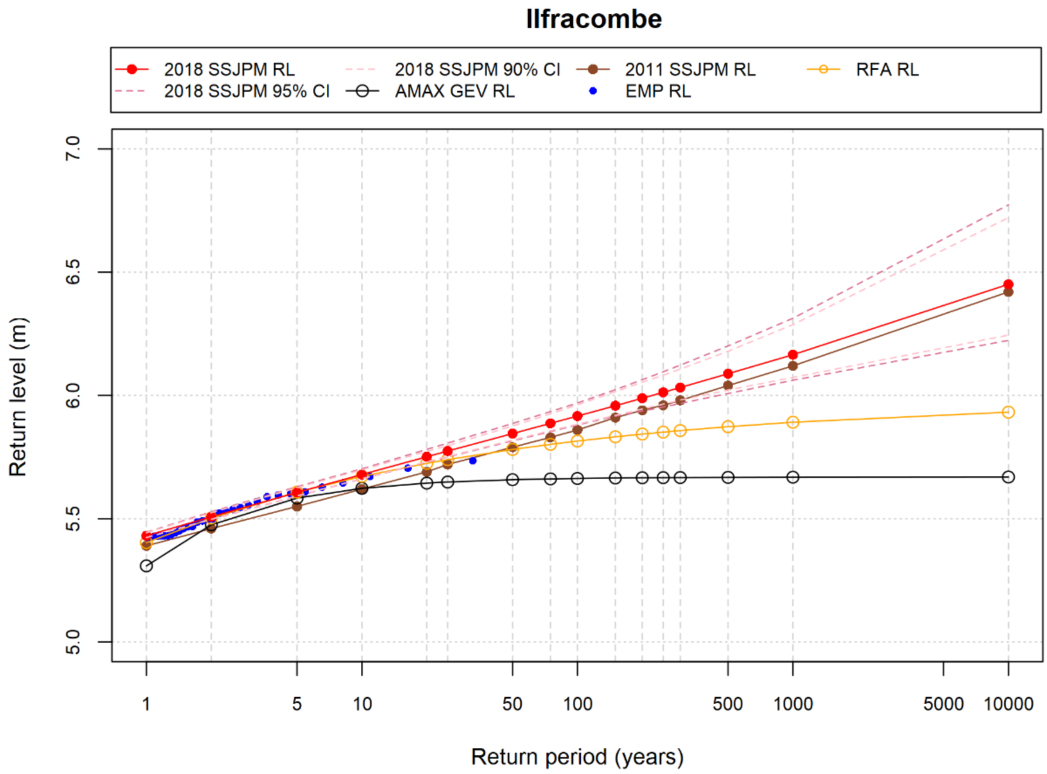


Figure F.5: Comparison at Ilfracombe tide gauge site

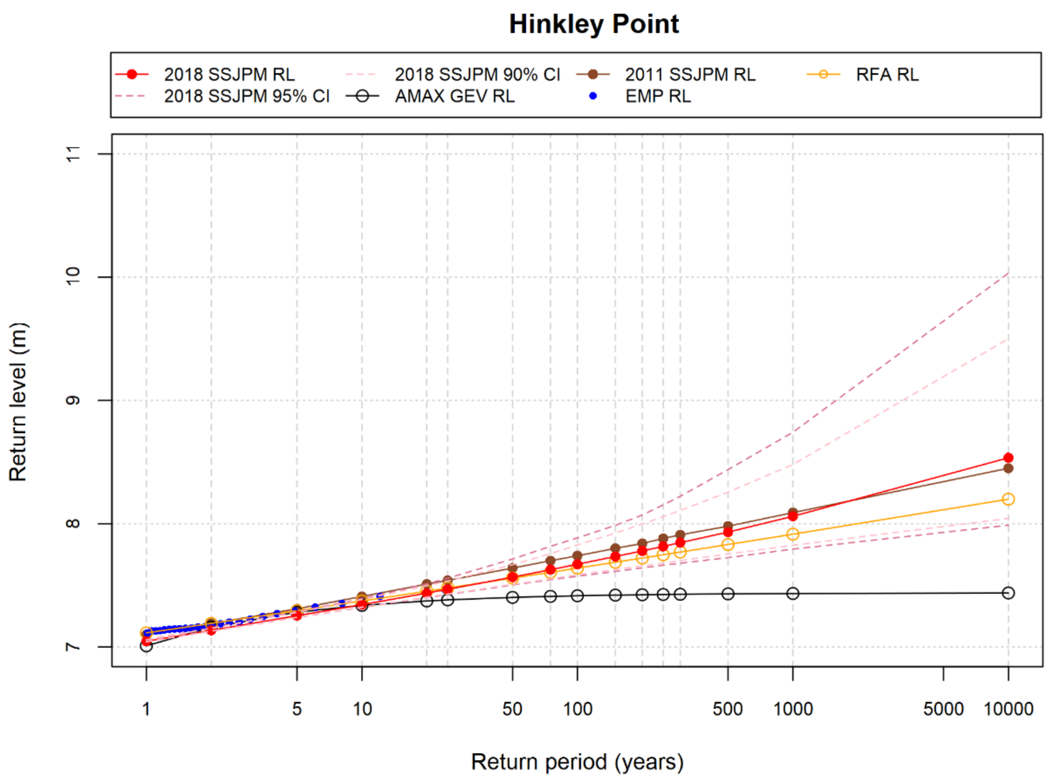


Figure F.6: Comparison at Hinckley Point tide gauge site

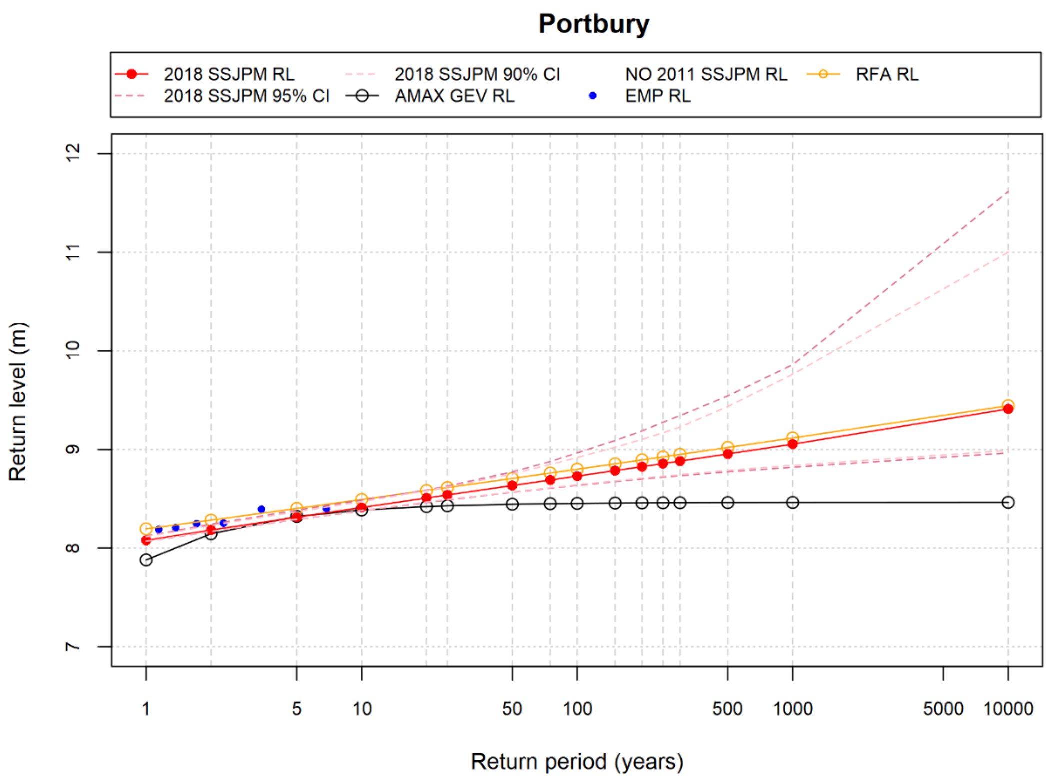


Figure F.7: Comparison at Portbury tide gauge site

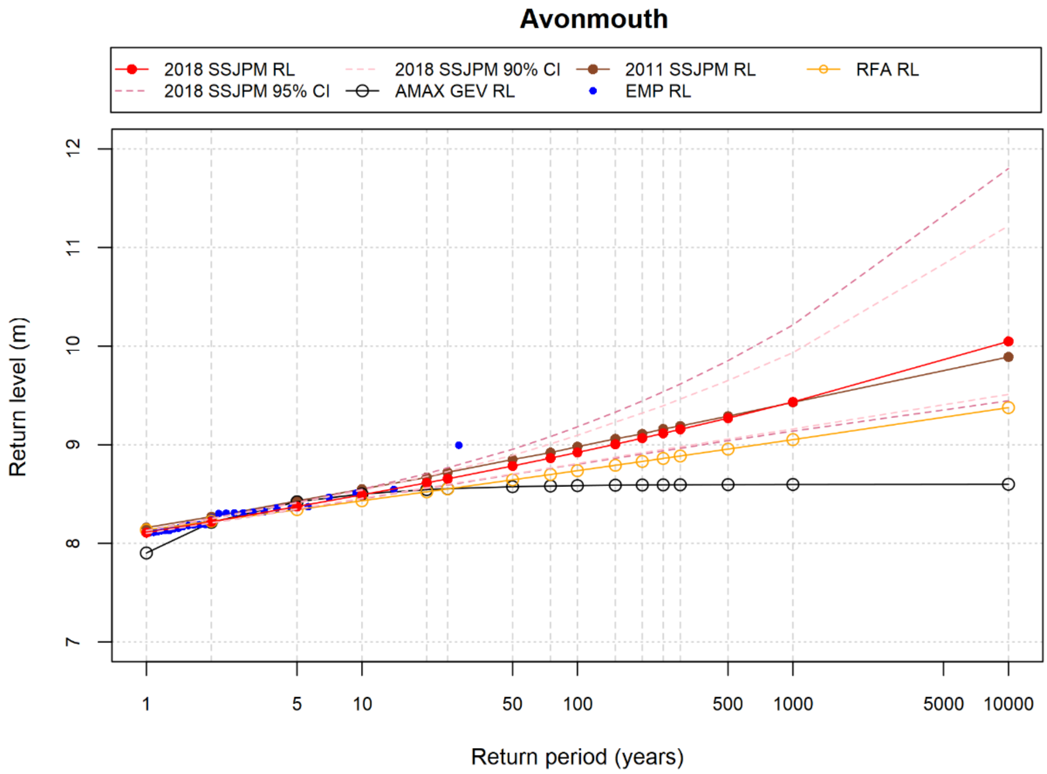


Figure F.8: Comparison at Avonmouth tide gauge site

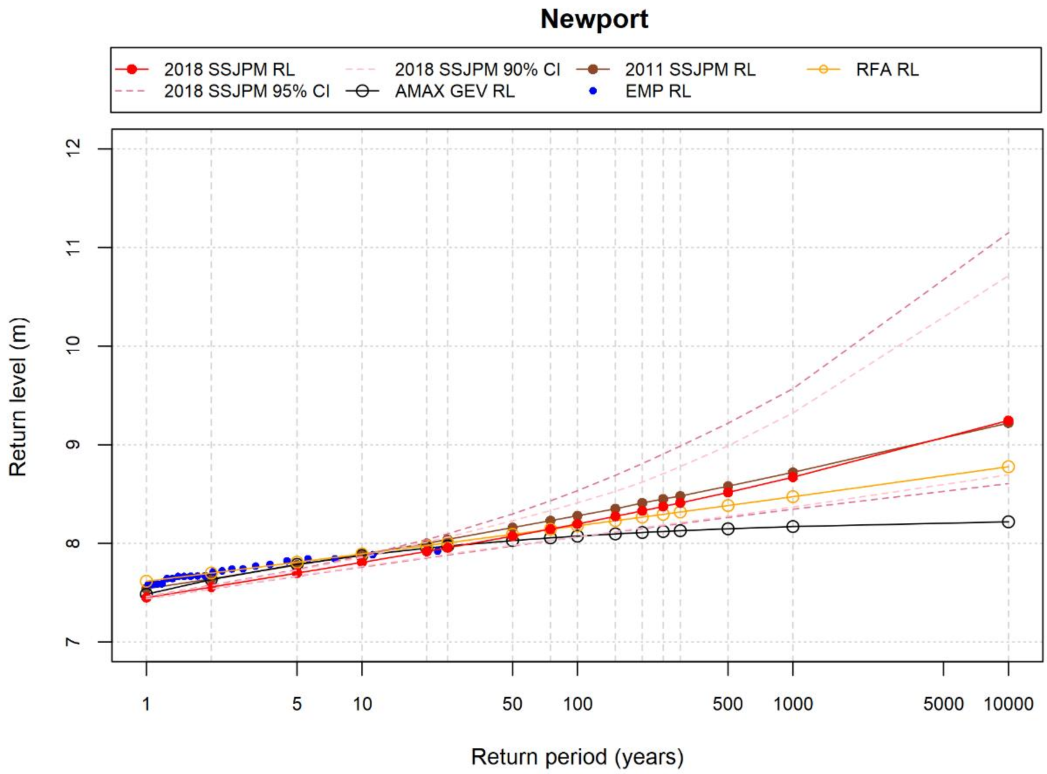


Figure F.9: Comparison at Newport tide gauge site

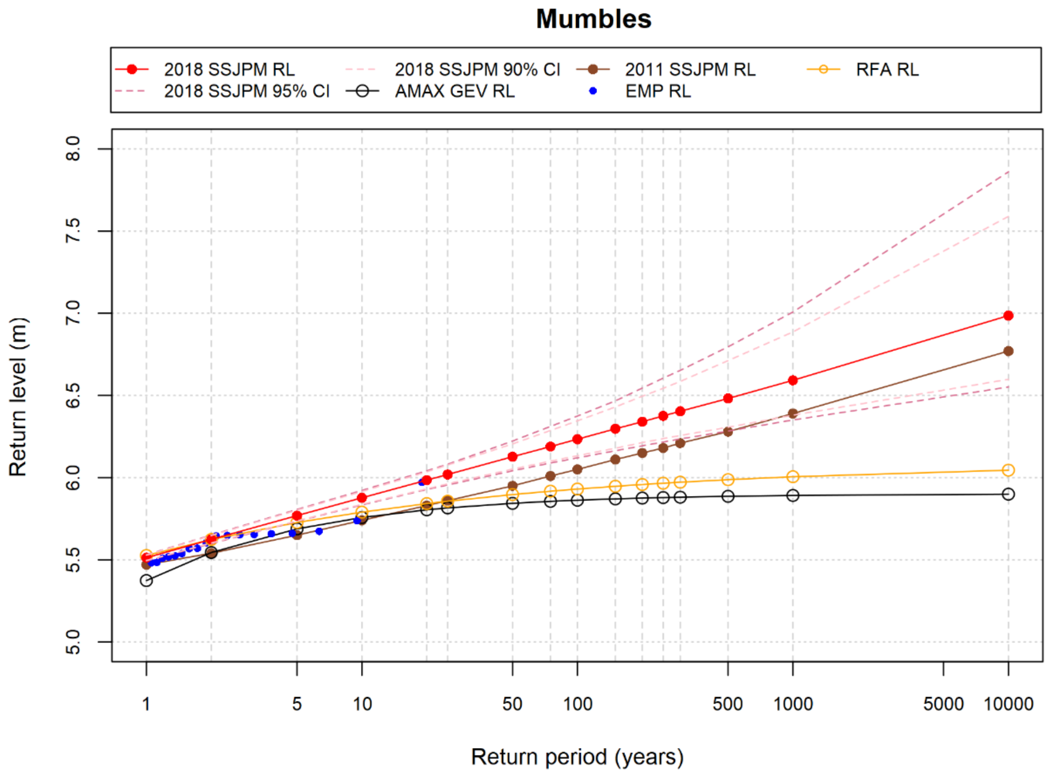


Figure F.10: Comparison at Mumbles tide gauge site

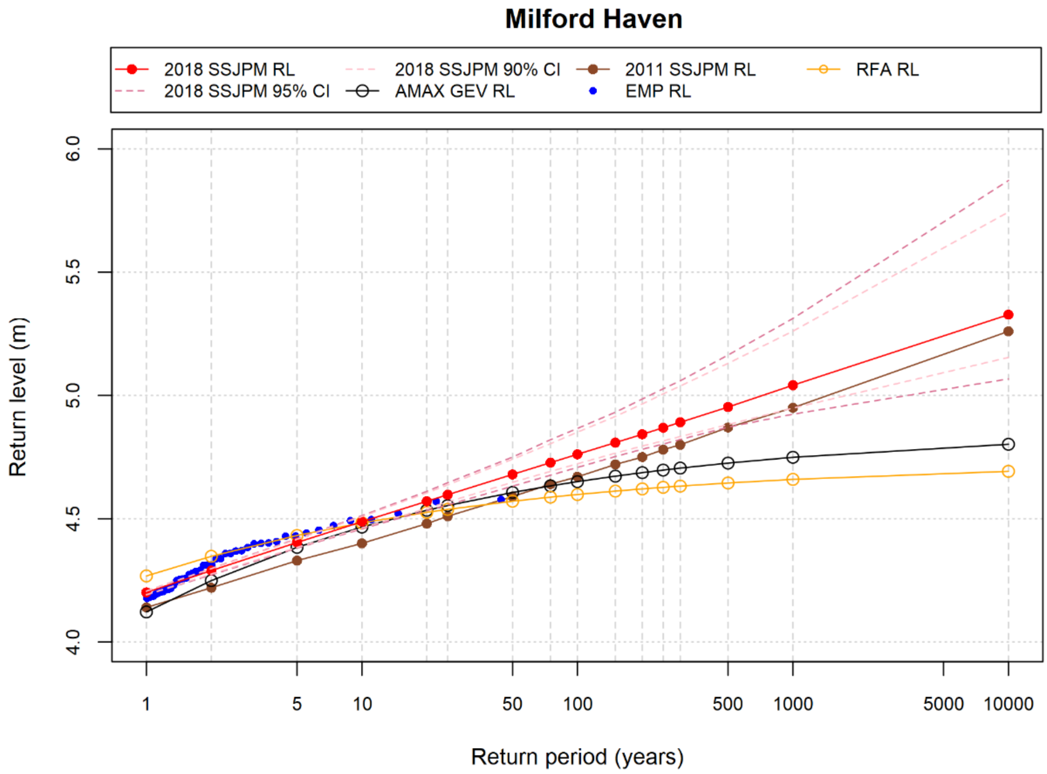


Figure F.11: Comparison at Milford Haven tide gauge site

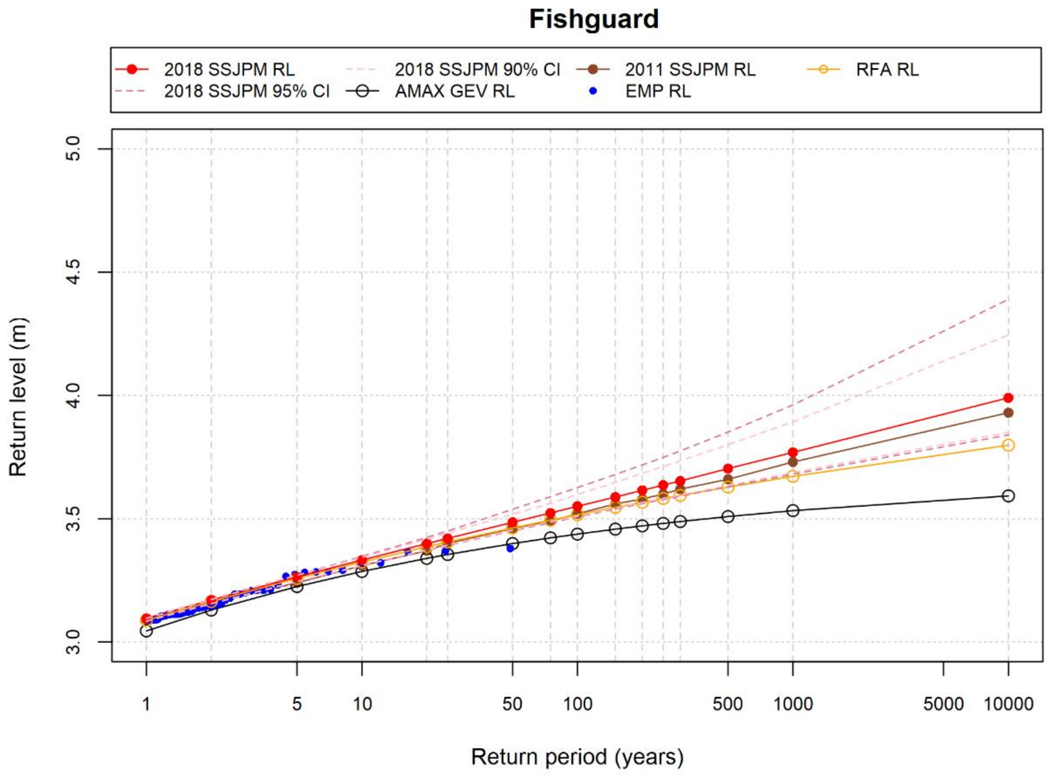


Figure F.12: Comparison at Fishguard tide gauge site

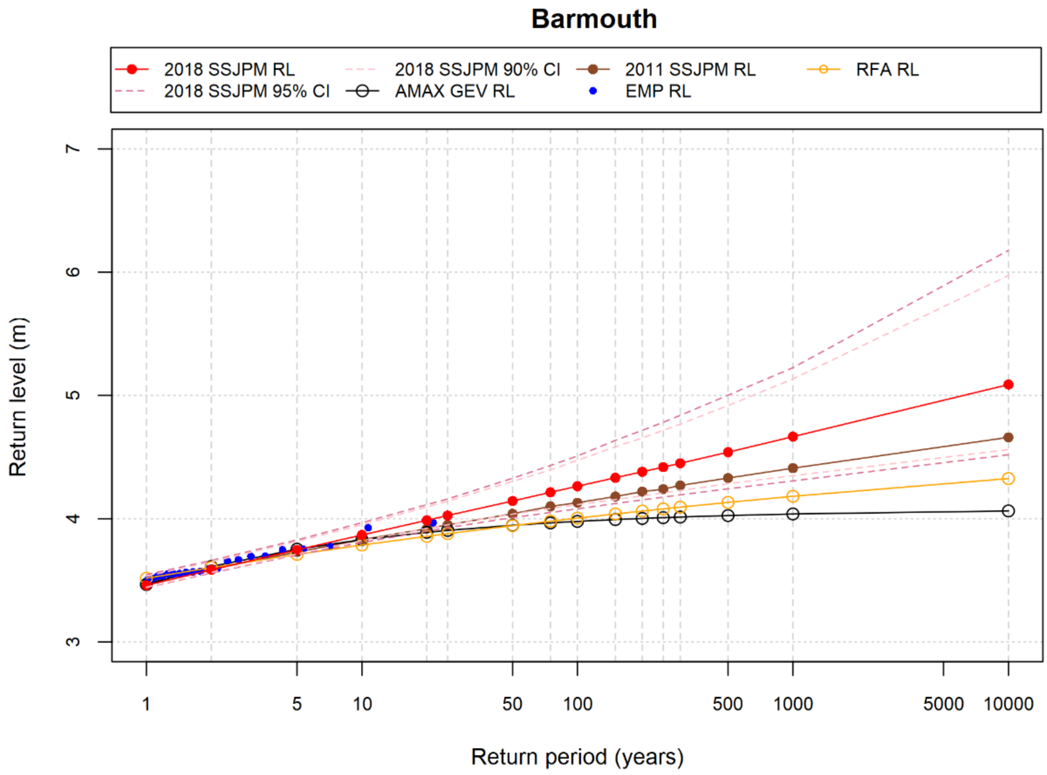


Figure F.13: Comparison at Barmouth tide gauge site

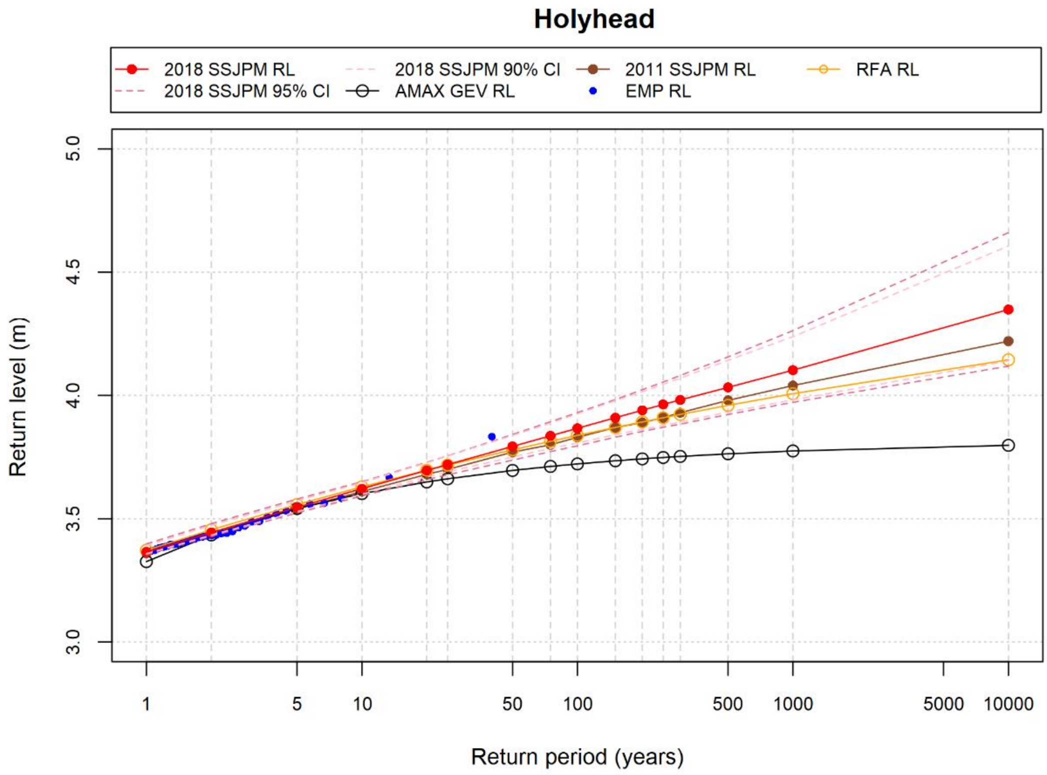


Figure F.14: Comparison at Holyhead tide gauge site

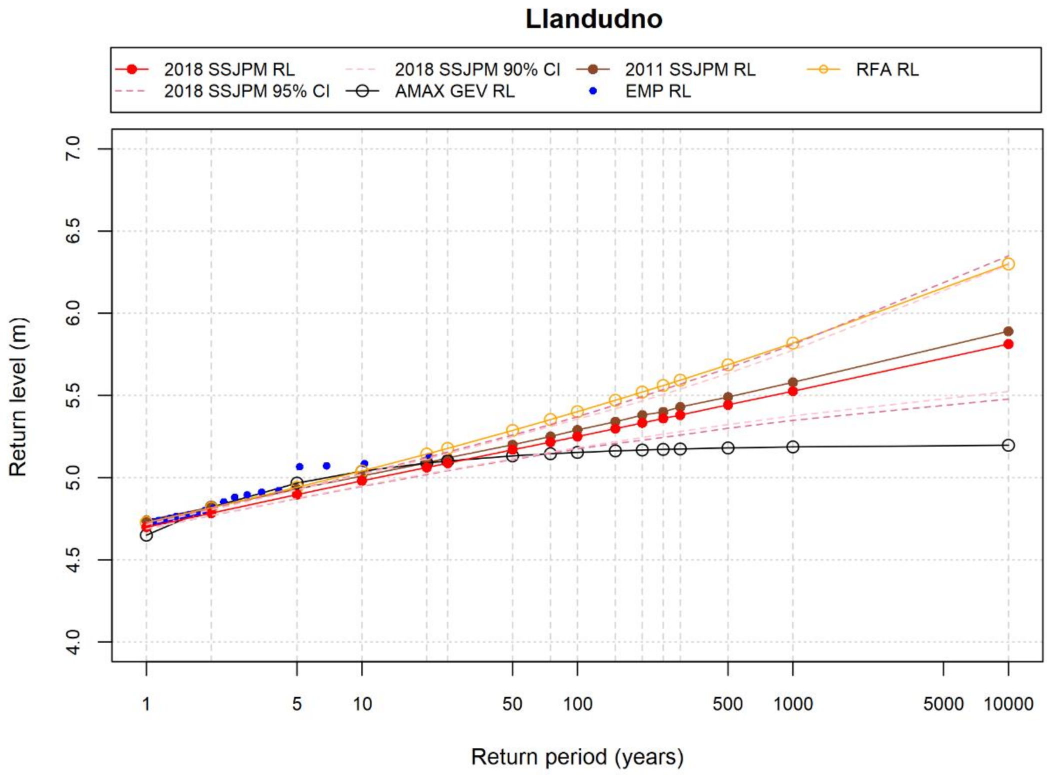


Figure F.15: Comparison at Llandudno tide gauge site

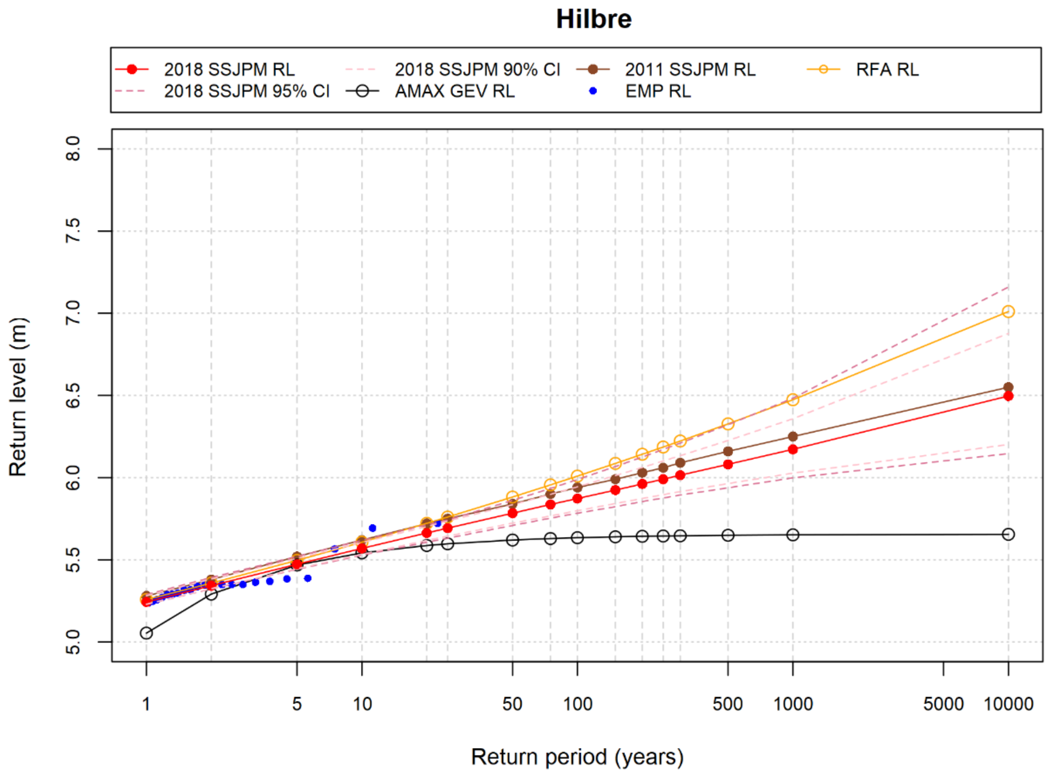


Figure F.16: Comparison at Hilbre tide gauge site

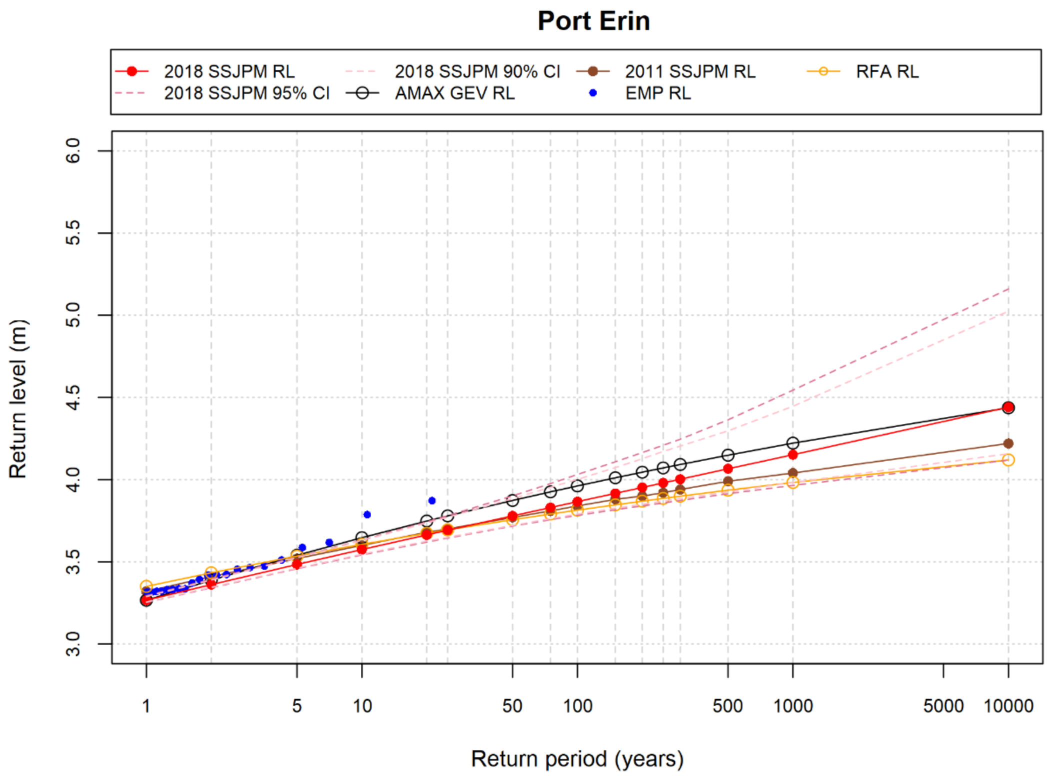


Figure F.17: Comparison at Port Erin (Isle of Man) tide gauge site

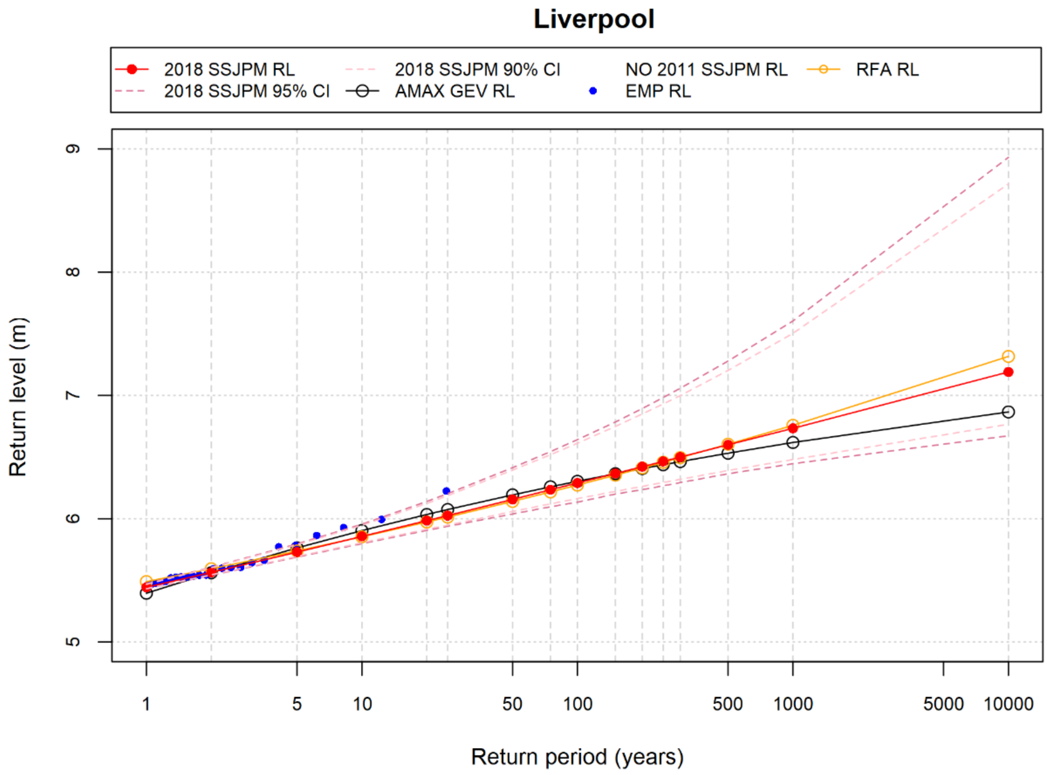


Figure F.18: Comparison at Liverpool (Gladstone Dock) tide gauge site

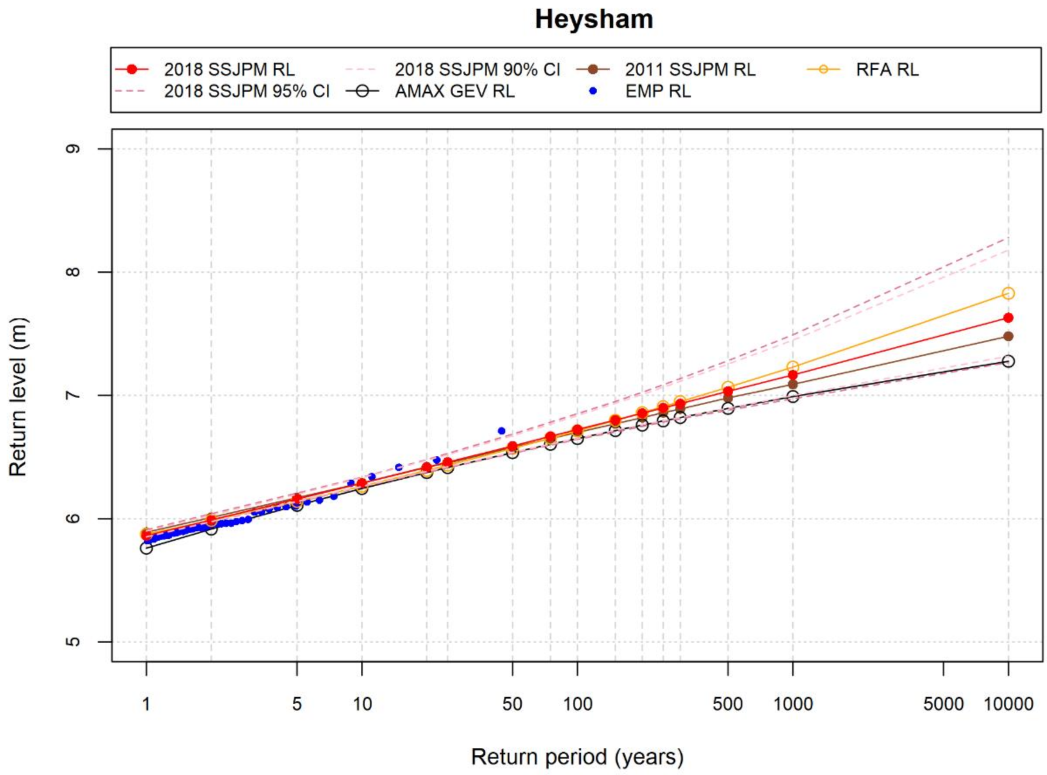


Figure F.19: Comparison at Heysham tide gauge site

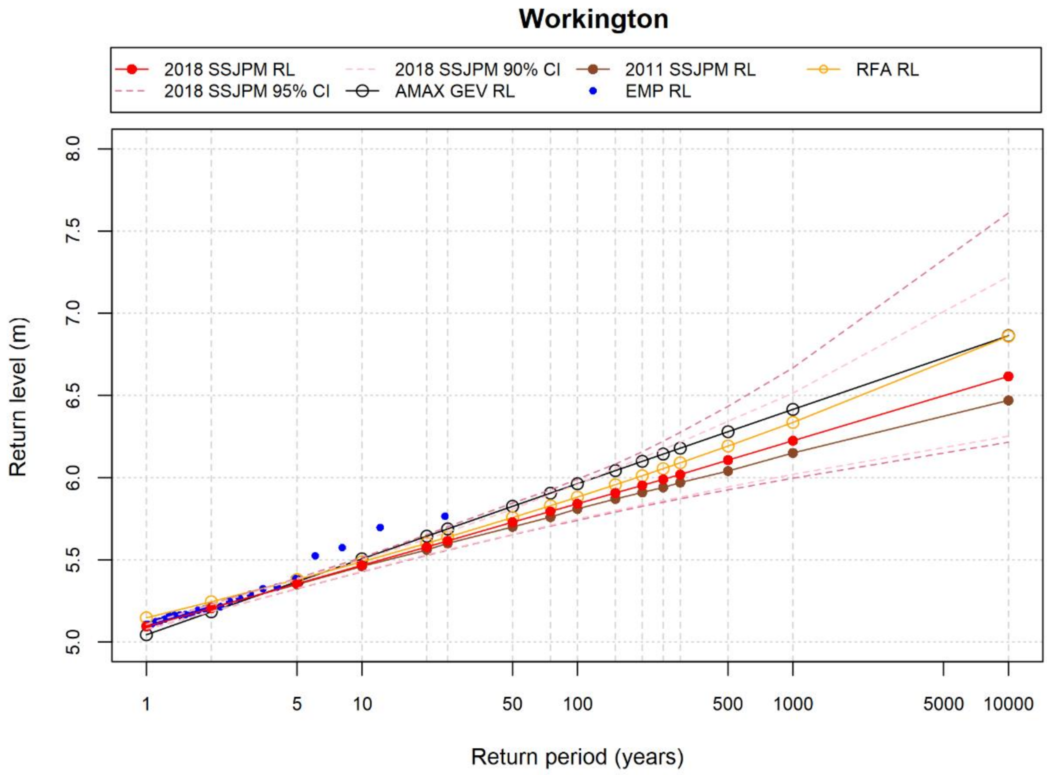


Figure F.20: Comparison at Workington tide gauge site

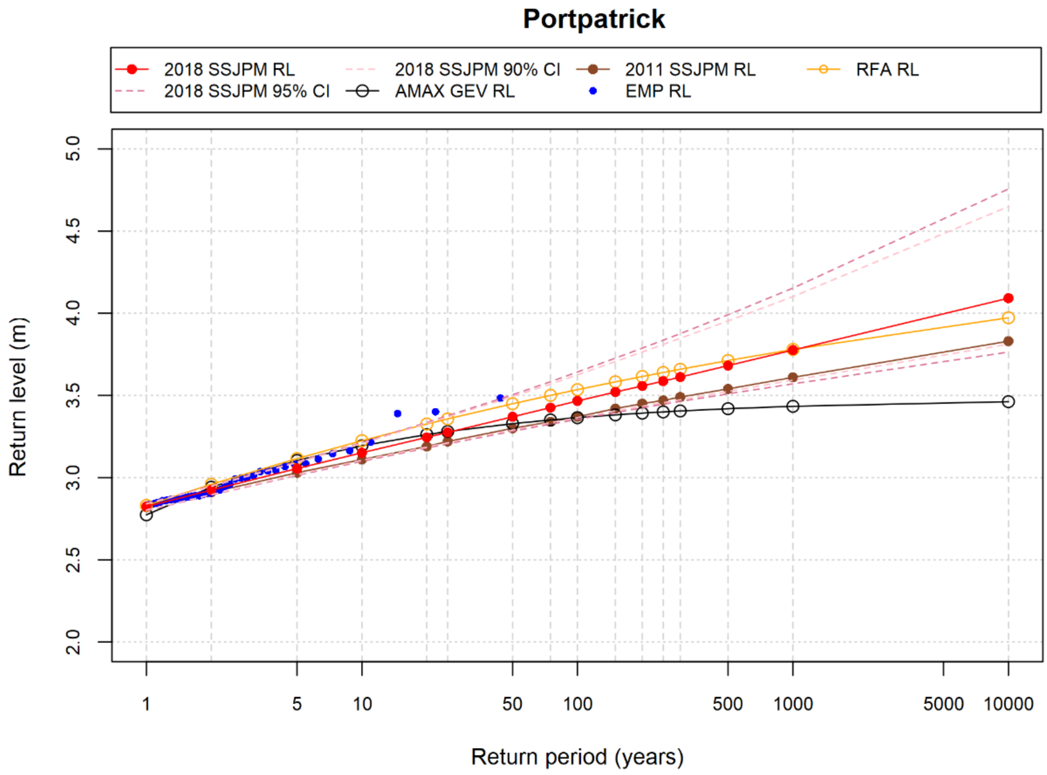


Figure F.21: Comparison at Portpatrick tide gauge site

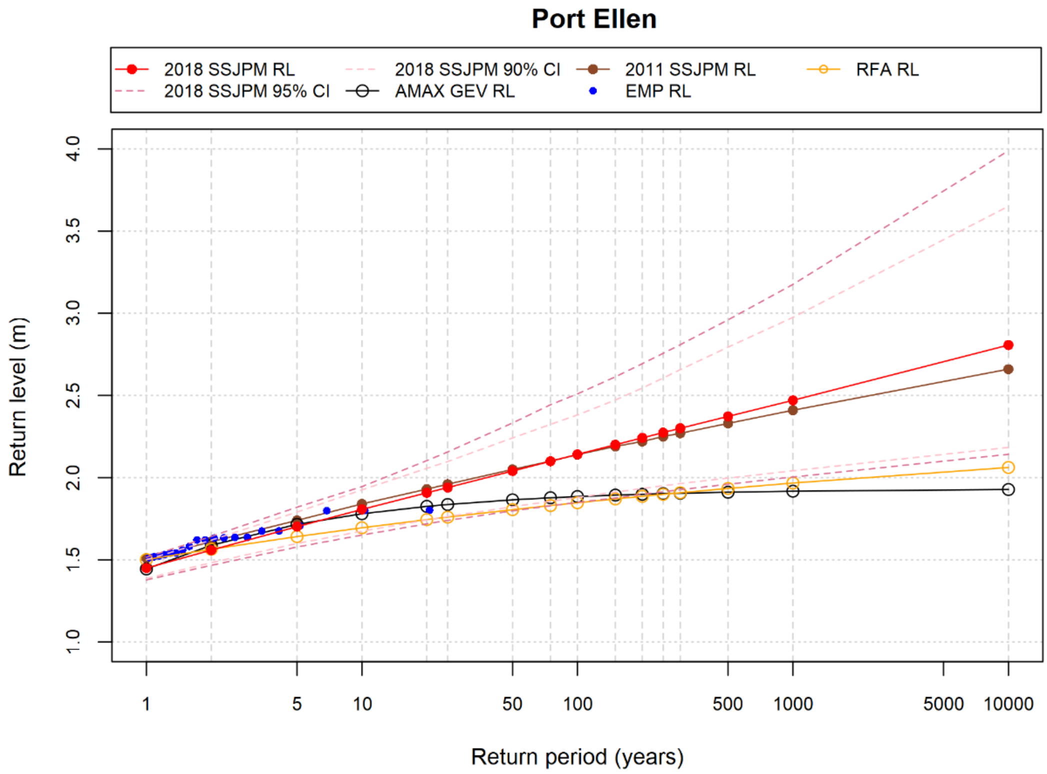


Figure F.22: Comparison at Port Ellen (Isle of Islay) tide gauge site

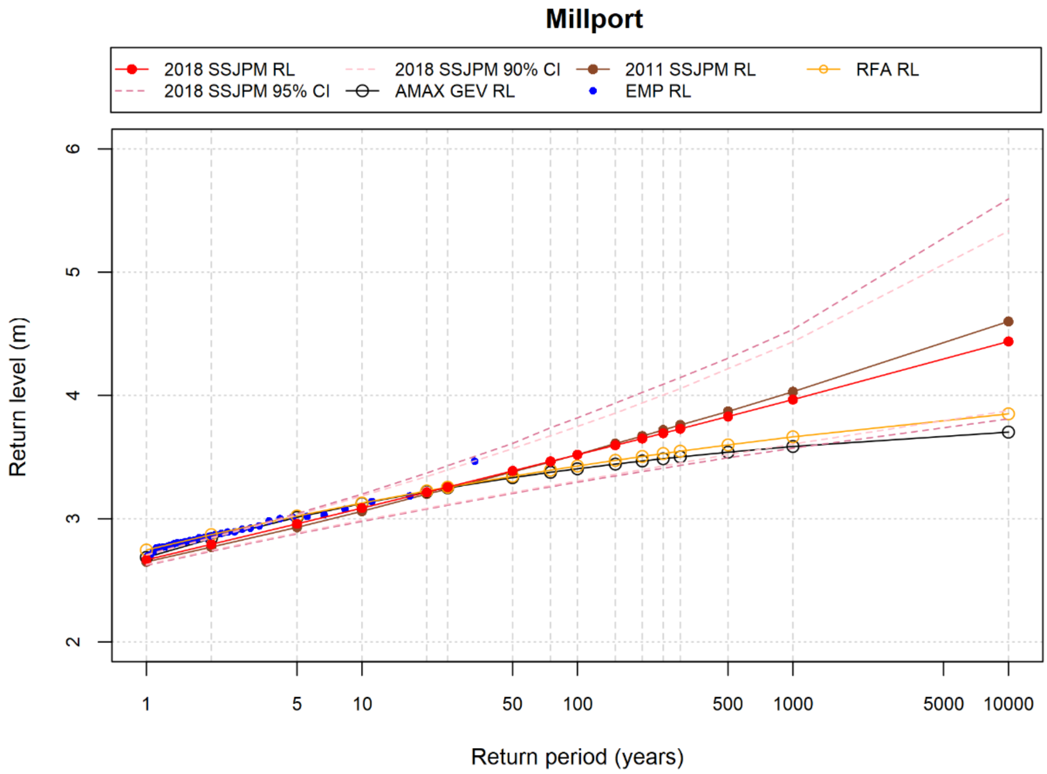


Figure F.23: Comparison at Millport tide gauge site

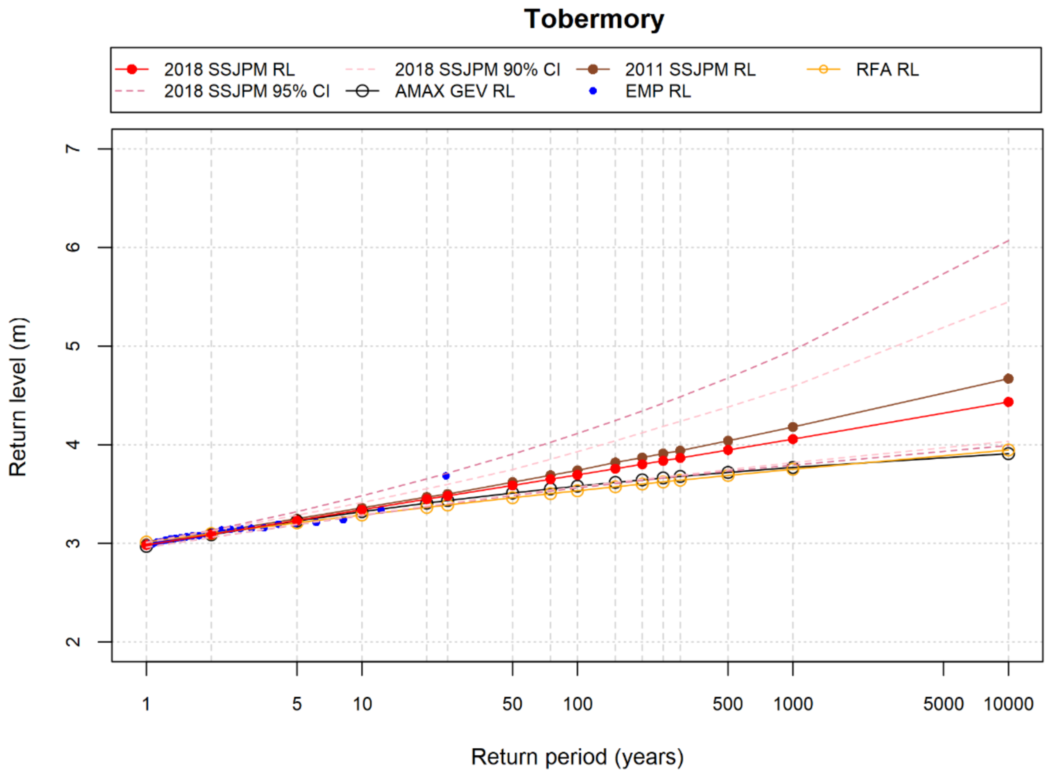


Figure F.24: Comparison at Tobermory (Isle of Mull) tide gauge site

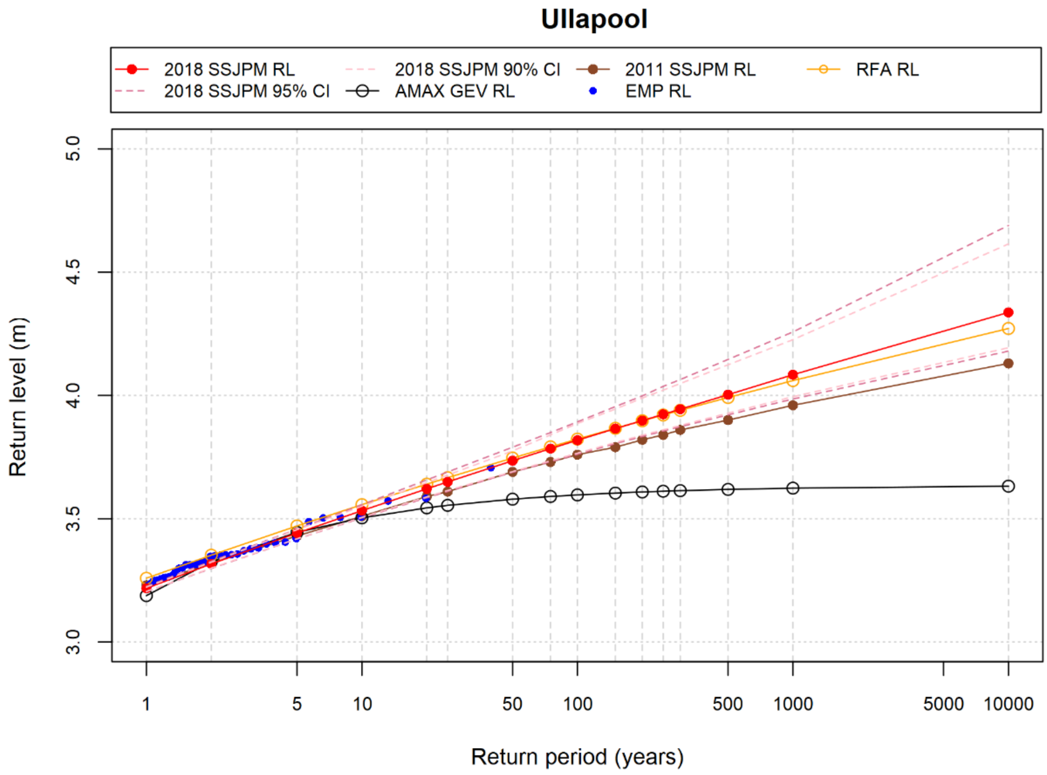


Figure F.25: Comparison at Ullapool tide gauge site

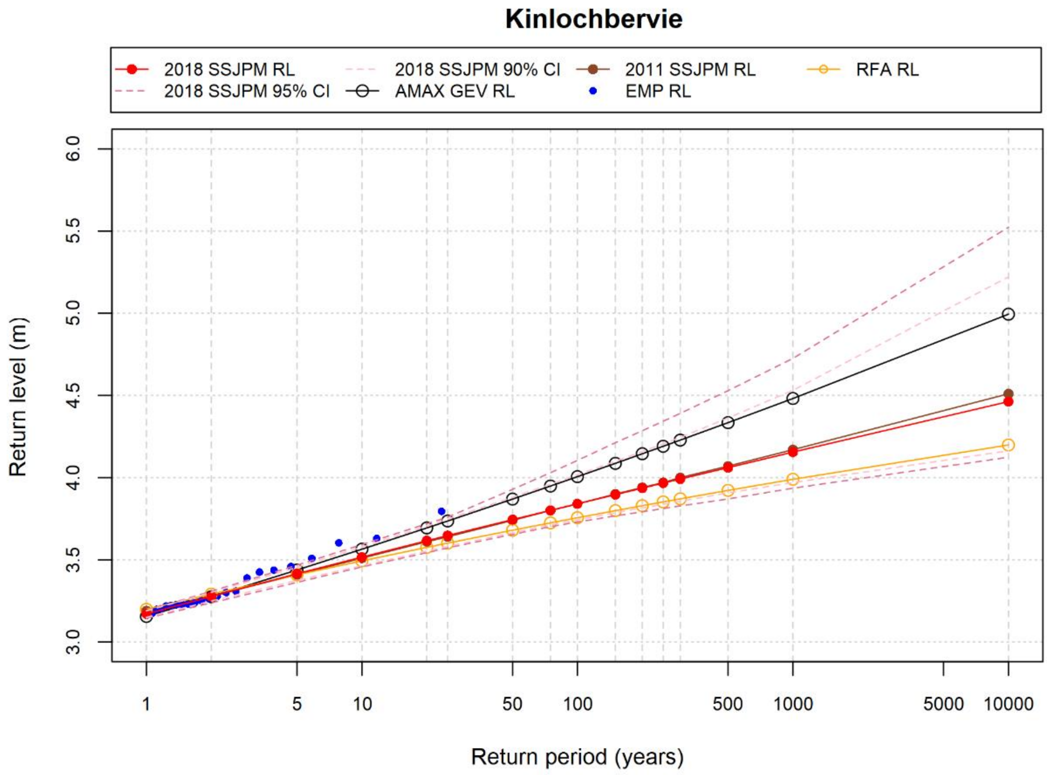


Figure F.26: Comparison at Kinlochbervie tide gauge site

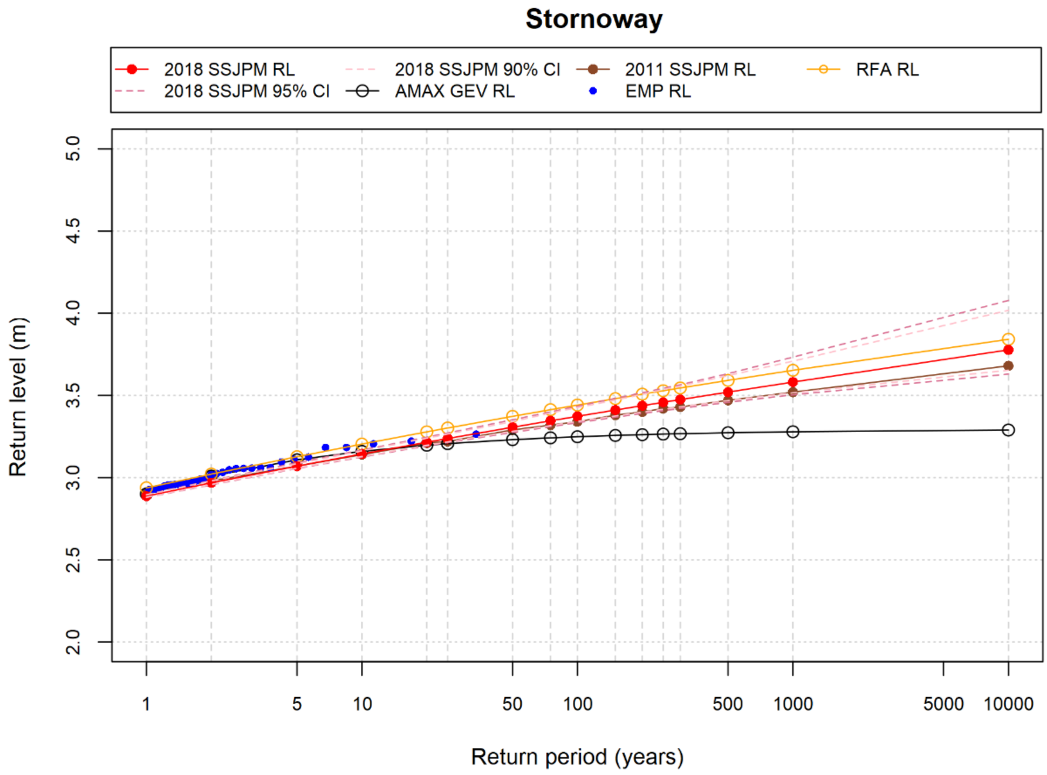


Figure F.27: Comparison at Stornaway (Hebrides) tide gauge site

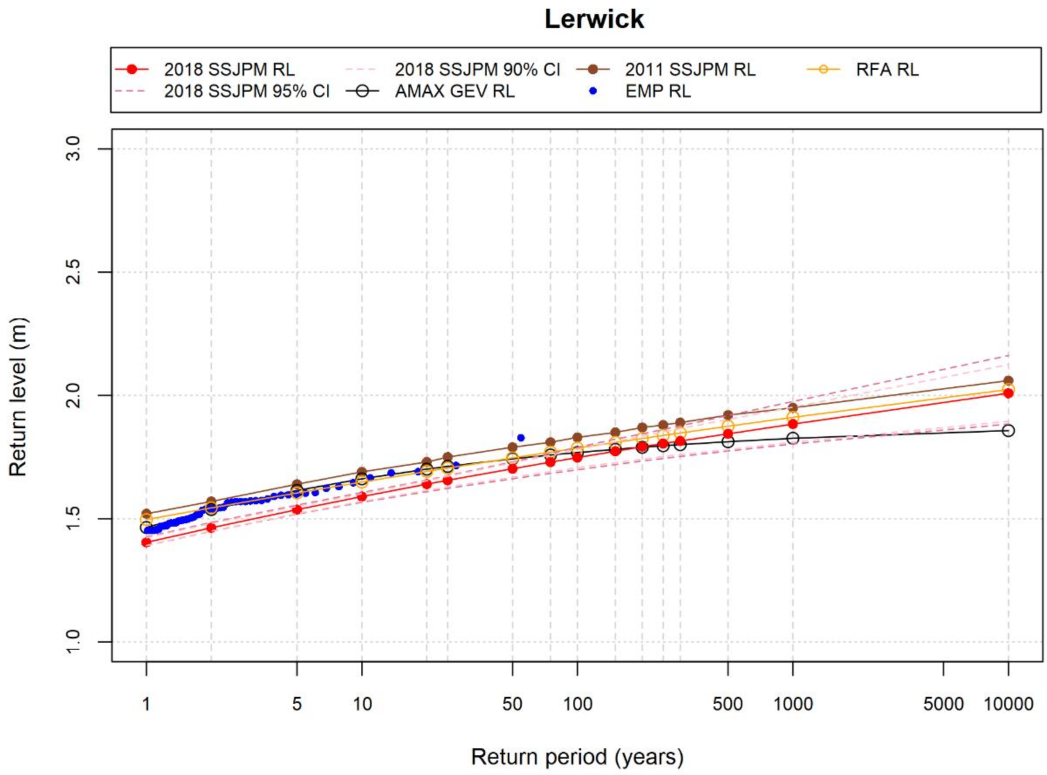


Figure F.28: Comparison at Lerwick (Shetland Isles) tide gauge site

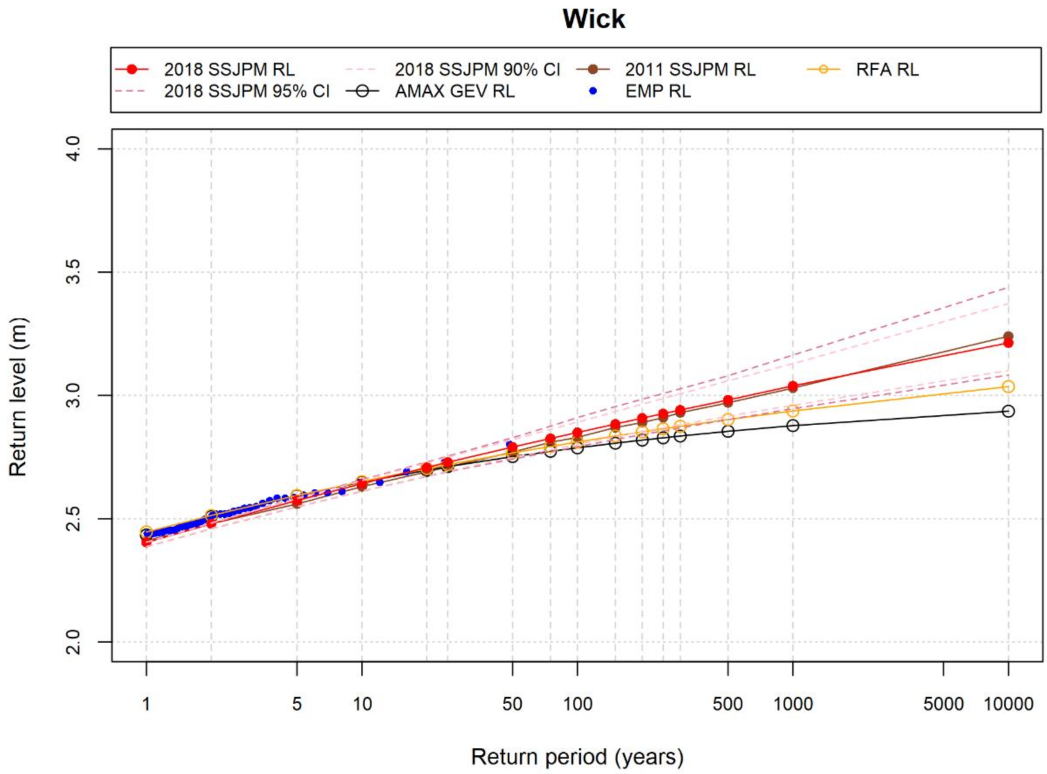


Figure F.29: Comparison at Wick tide gauge site

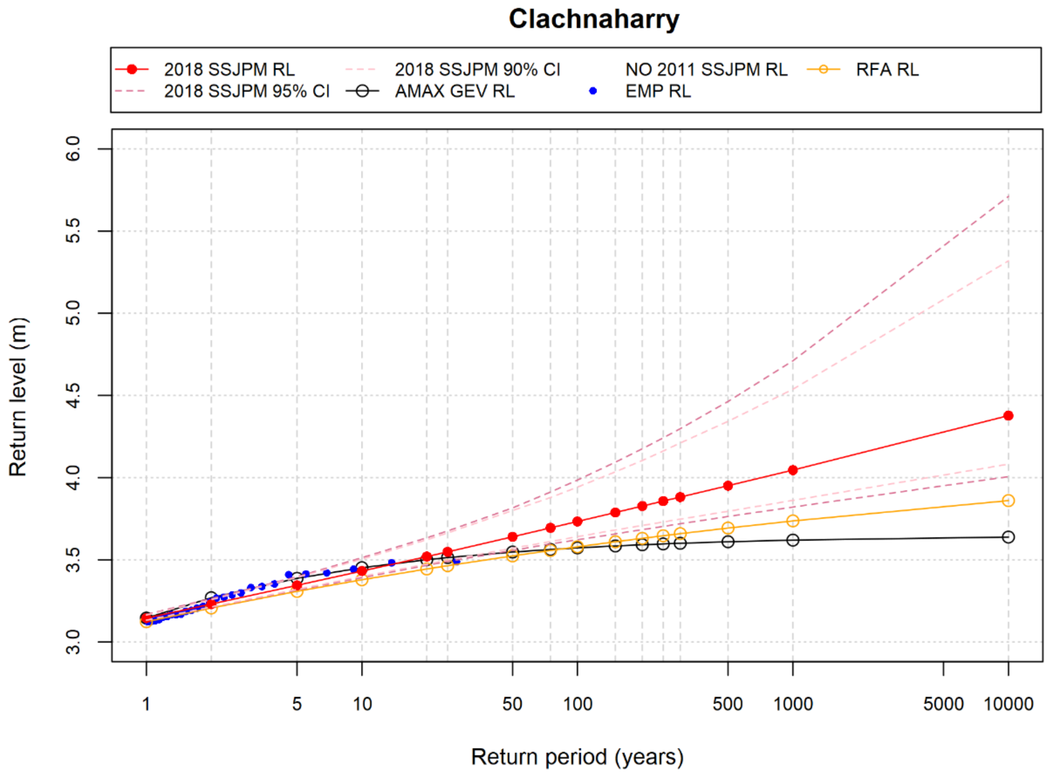


Figure F.30: Comparison at Clachnaharry tide gauge site

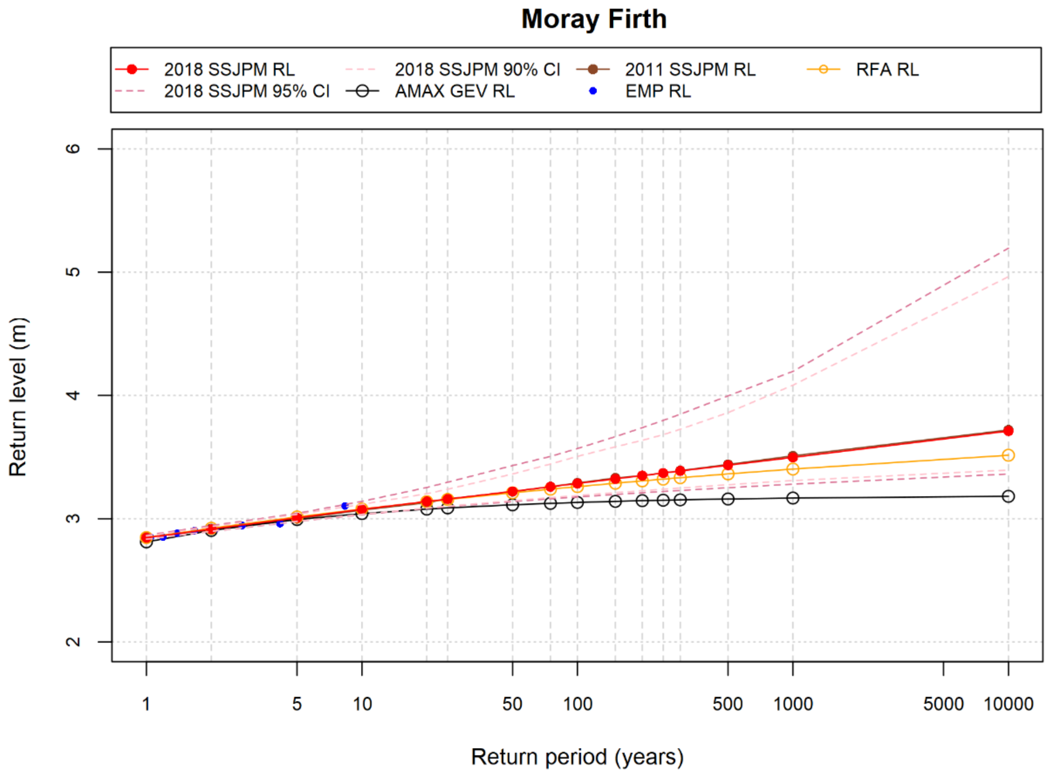


Figure F.31: Comparison at Moray Firth tide gauge site

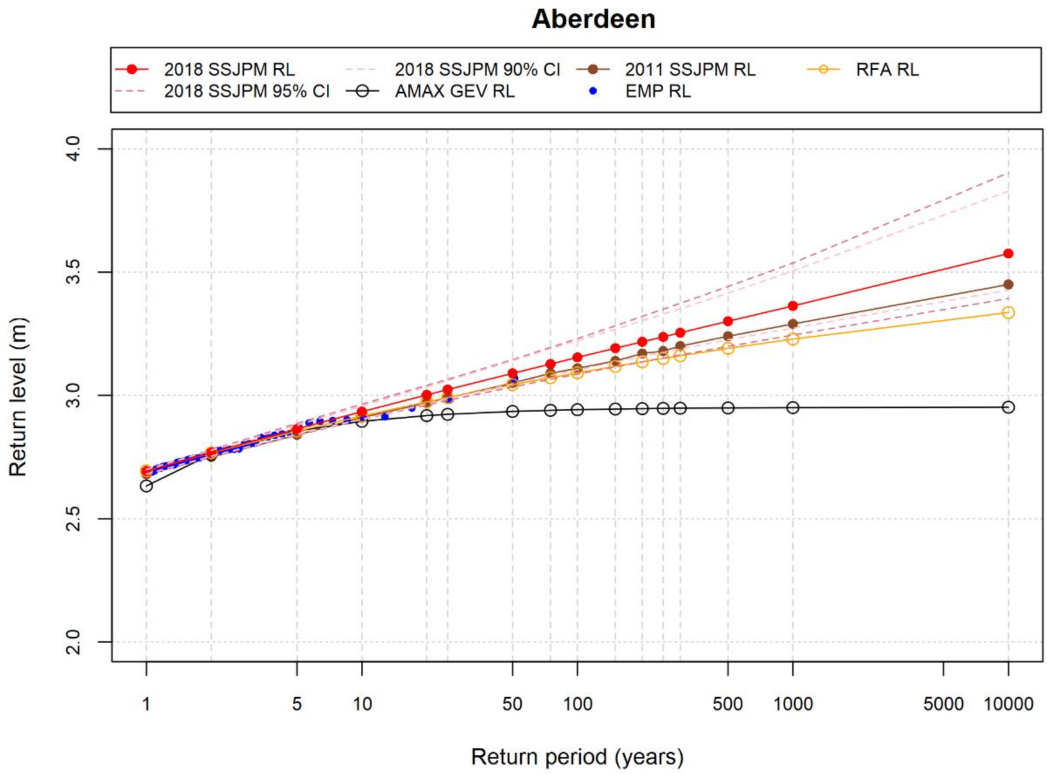


Figure F.32: Comparison at Aberdeen tide gauge site

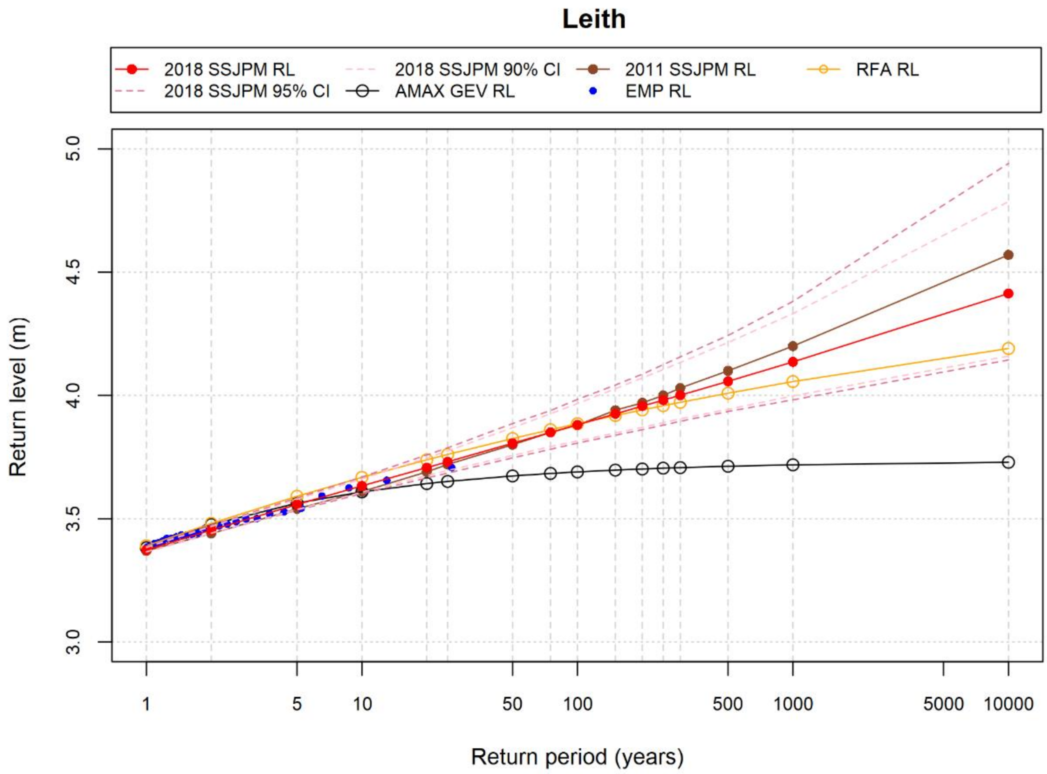


Figure F.33: Comparison at Leith tide gauge site

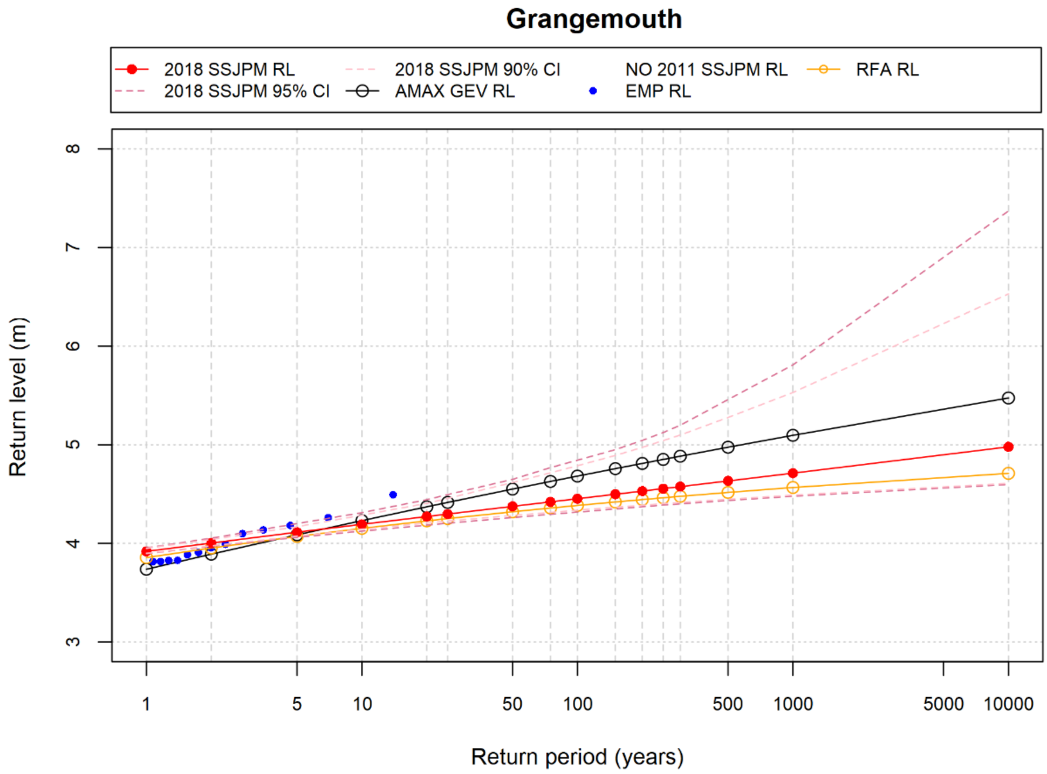


Figure F.34: Comparison at Grangemouth tide gauge site

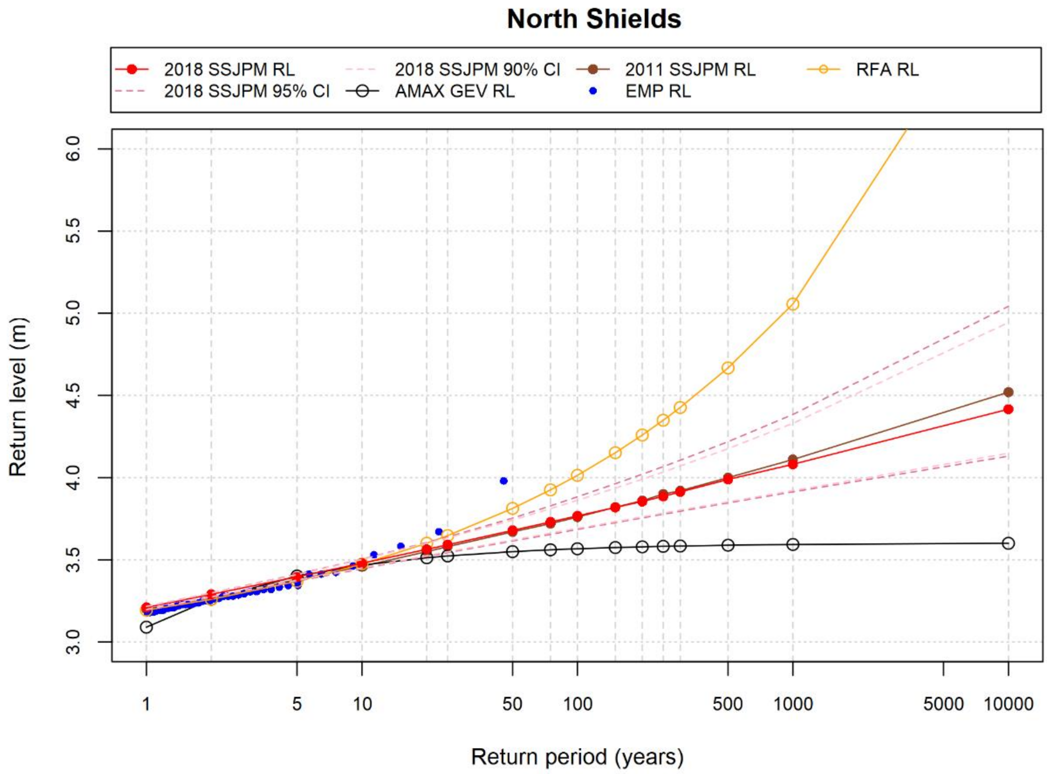


Figure F.35: Comparison at North Shields tide gauge site

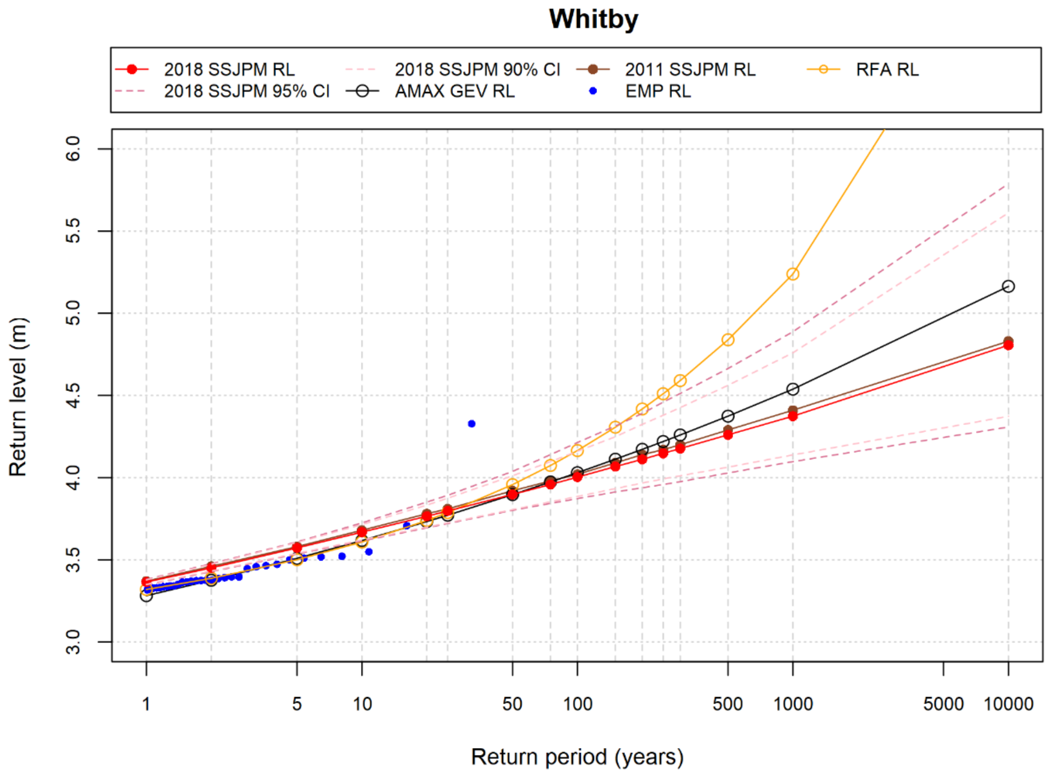


Figure F.36: Comparison at Whitby tide gauge site

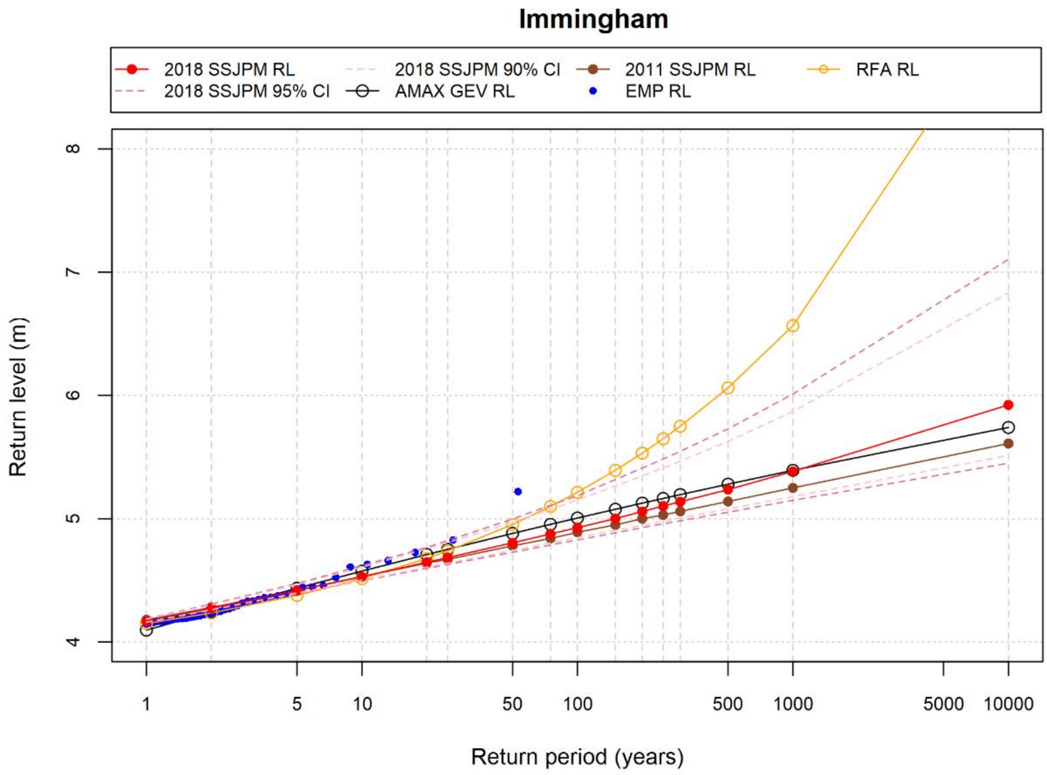


Figure F.37: Comparison at Immingham tide gauge site

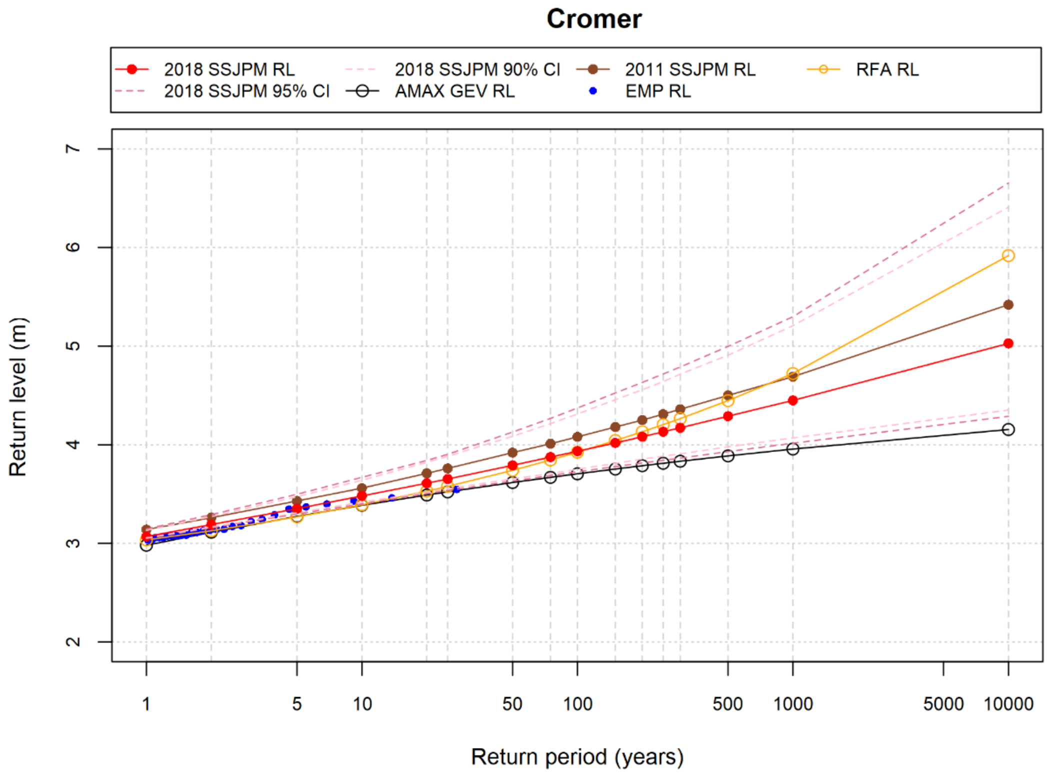


Figure F.38: Comparison at Cromer tide gauge site

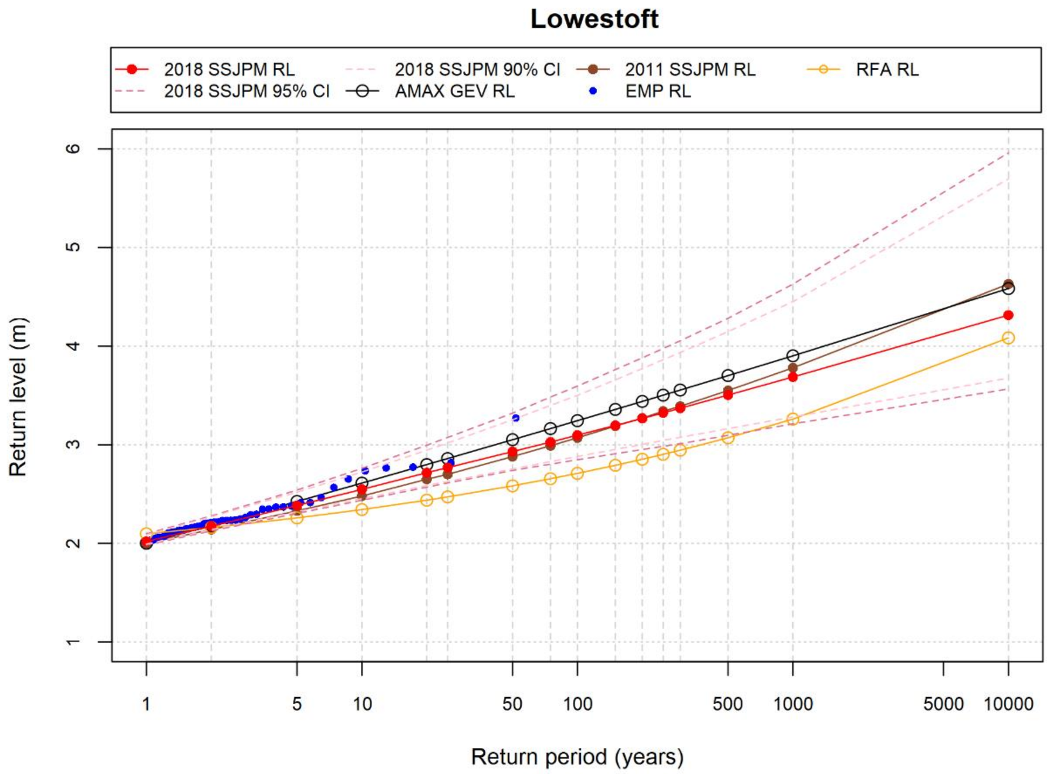


Figure F.39: Comparison at Lowestoft tide gauge site

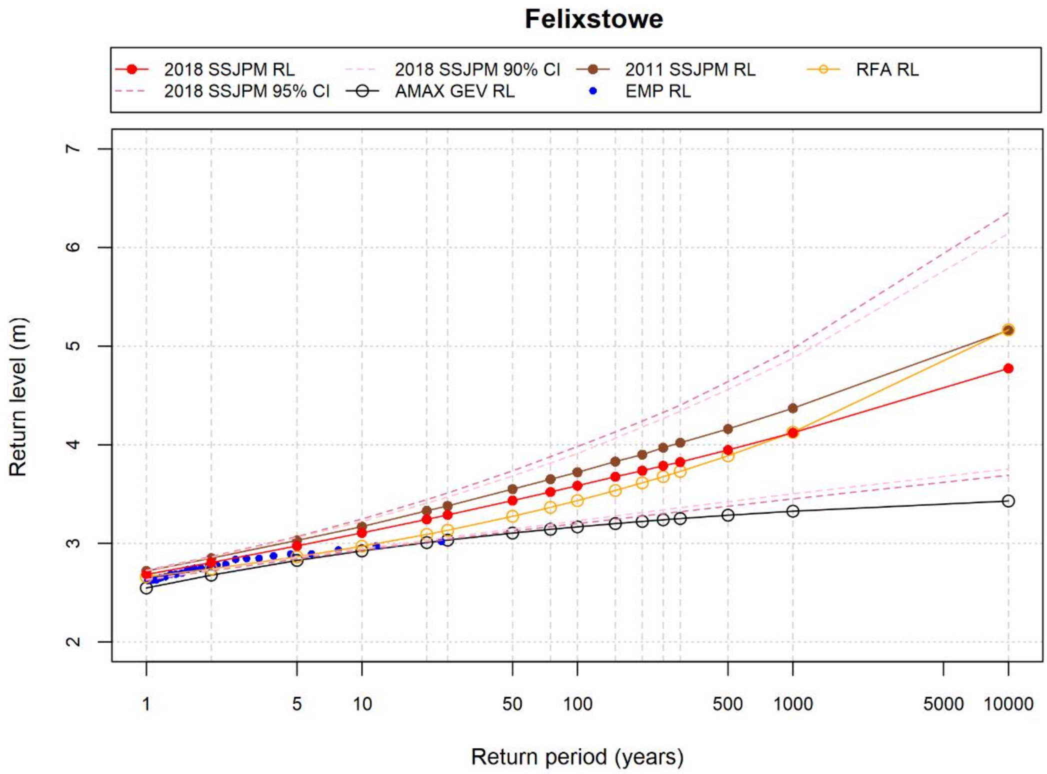


Figure F.40: Comparison at Felixstowe tide gauge site

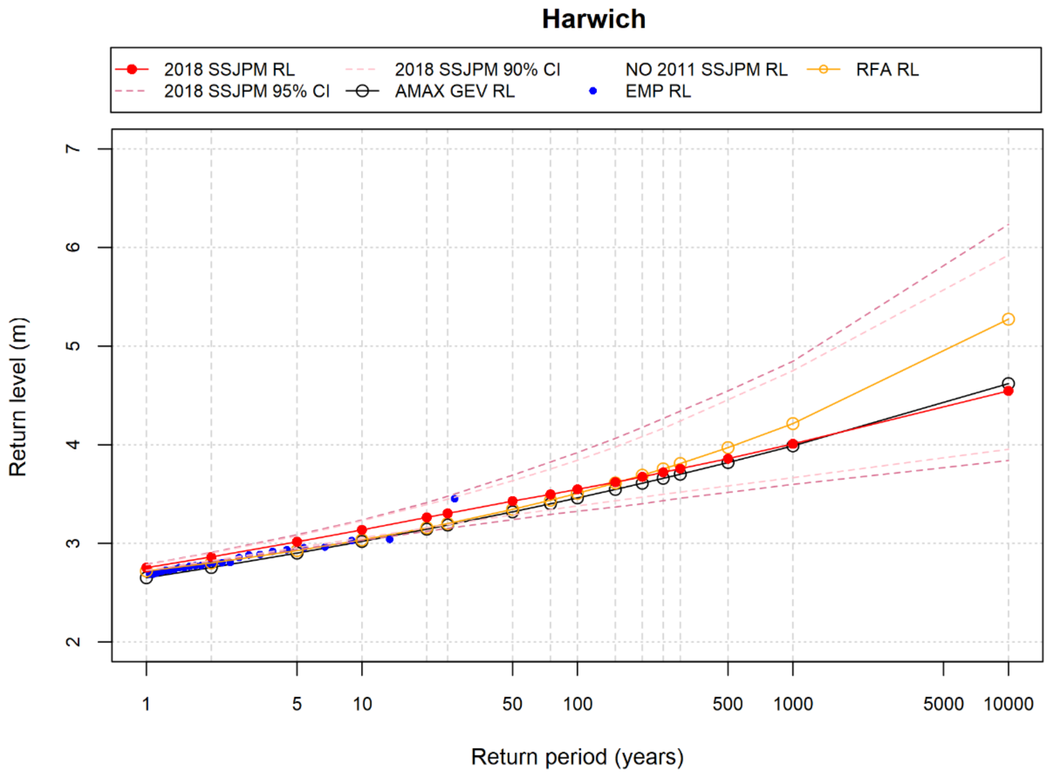


Figure F.41: Comparison at Harwich tide gauge site

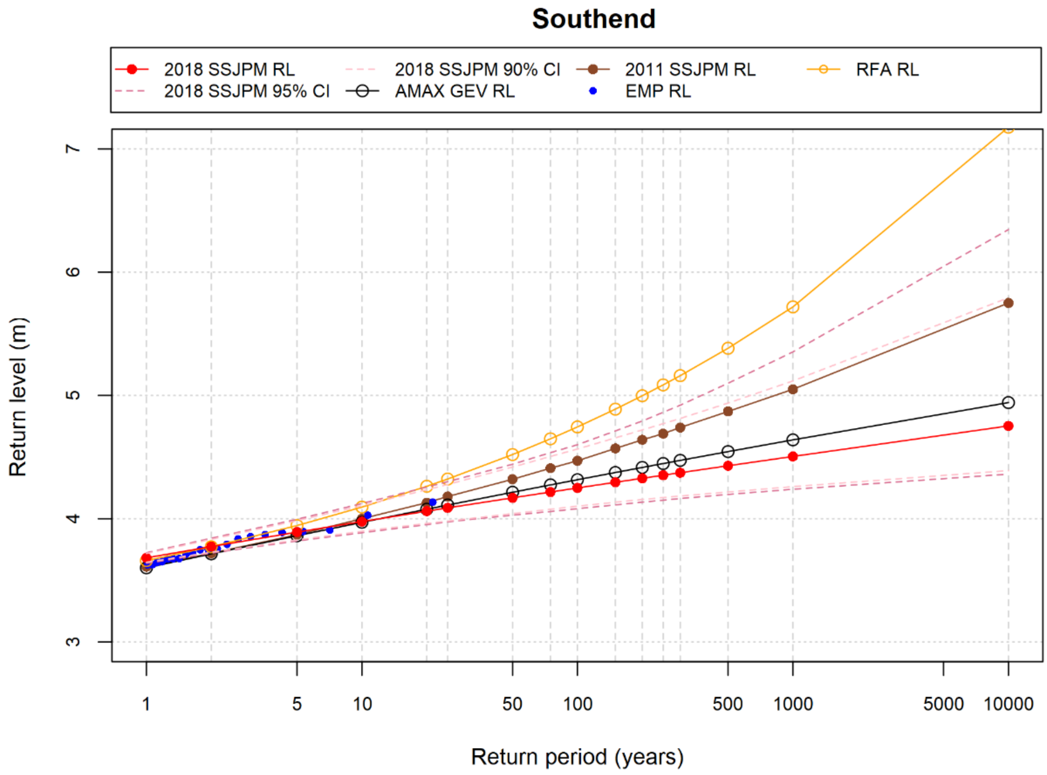


Figure F.42: Comparison at Southend tide gauge site

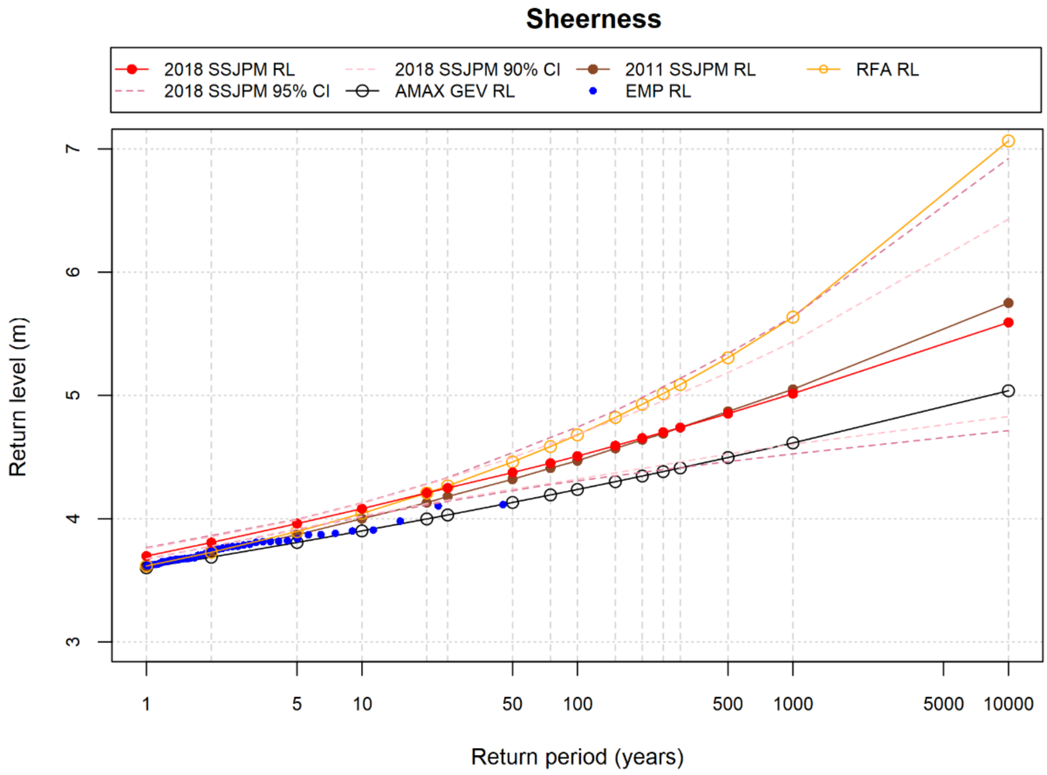


Figure F.43: Comparison at Sheerness tide gauge site

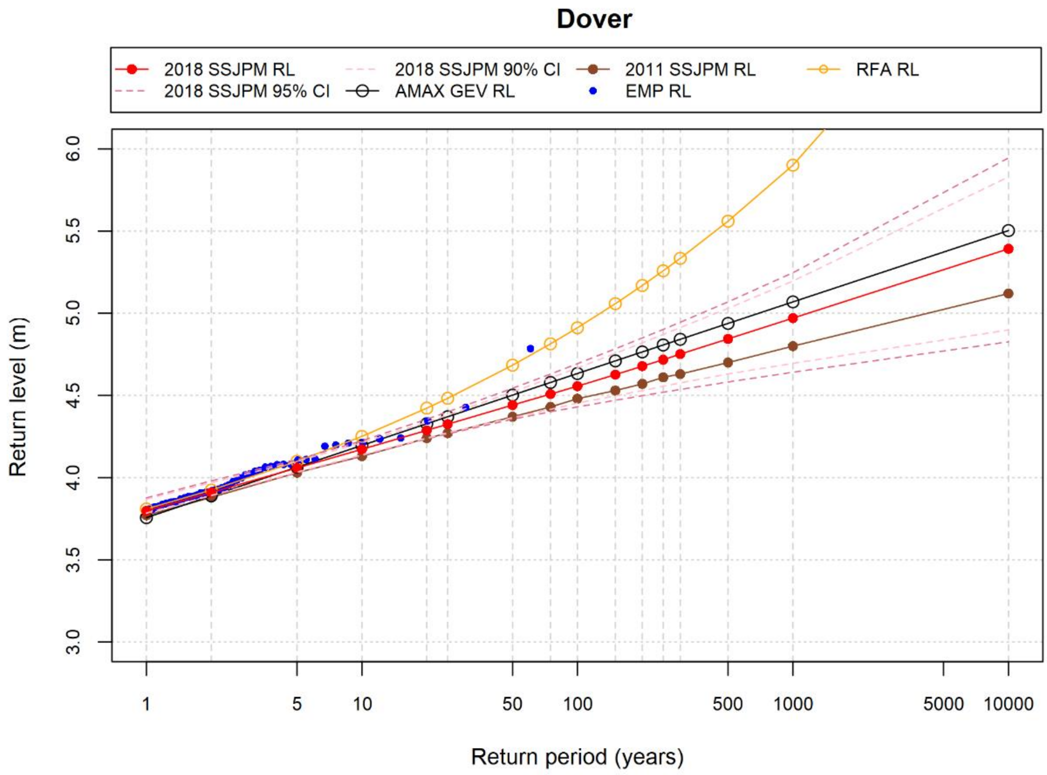


Figure F.44: Comparison at Dover tide gauge site

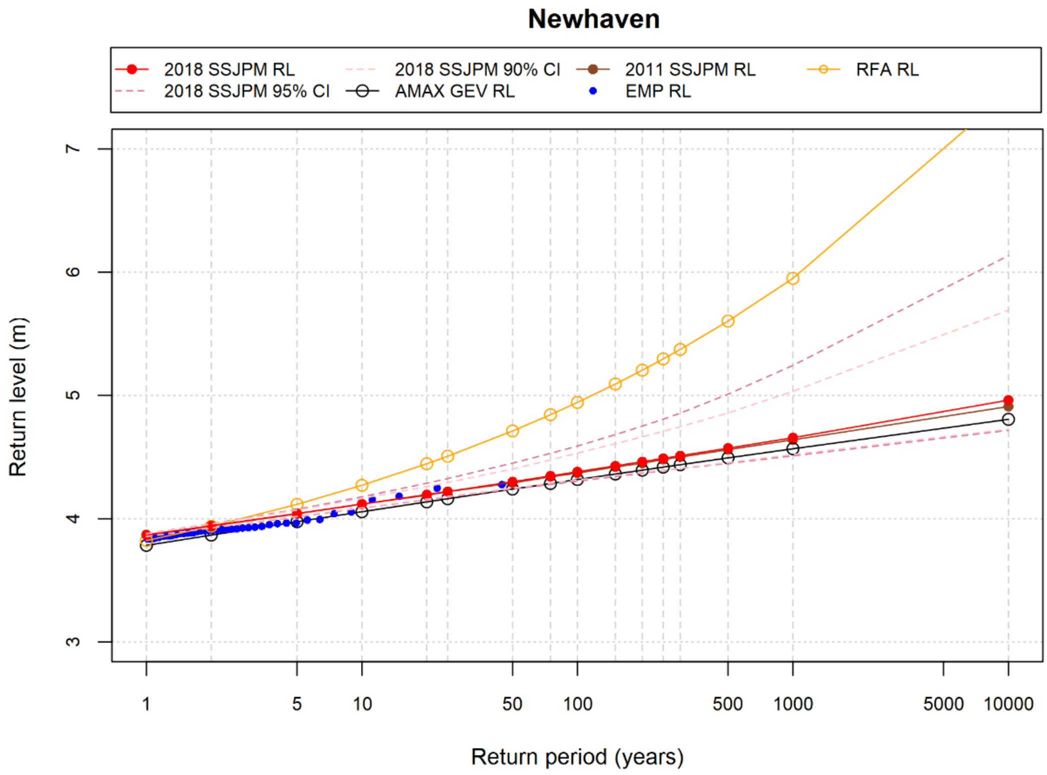


Figure F.45: Comparison at Newhaven tide gauge site

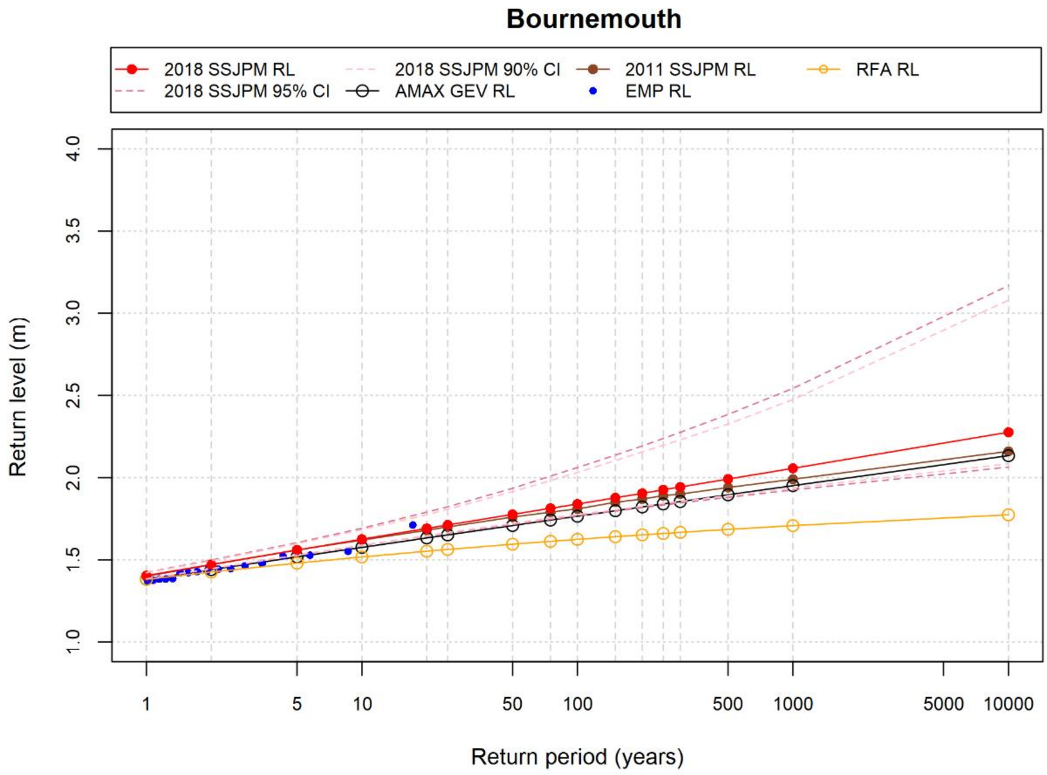


Figure F.46: Comparison at Bournemouth tide gauge site

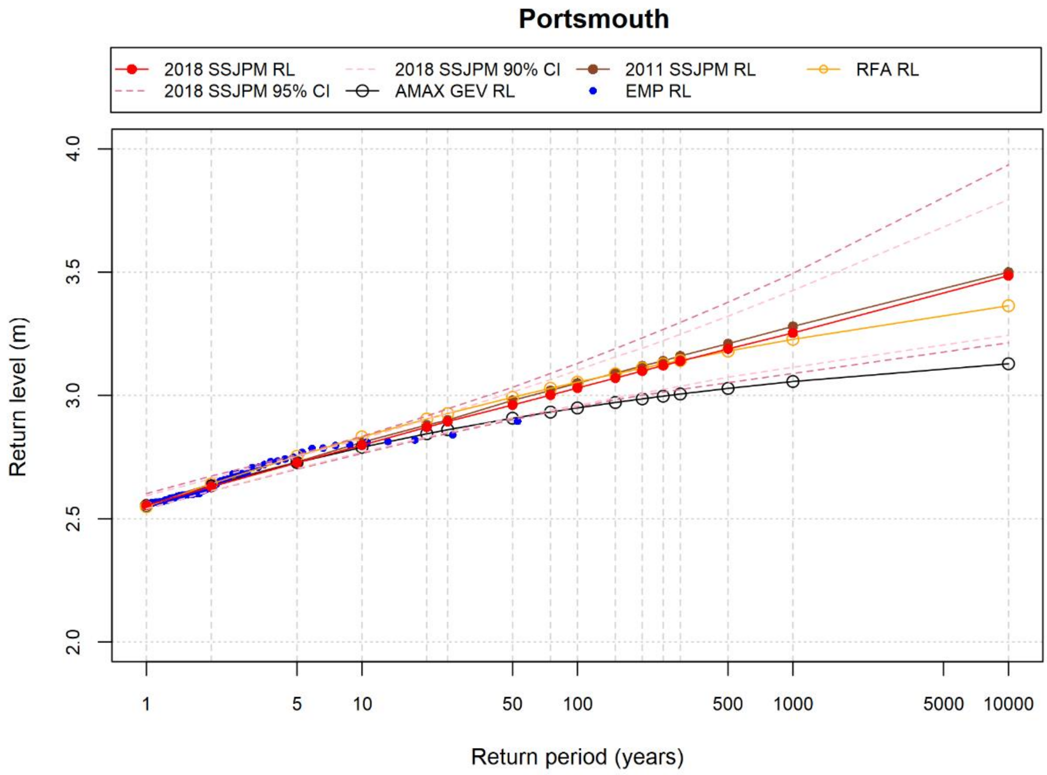


Figure F.47: Comparison at Portsmouth tide gauge site

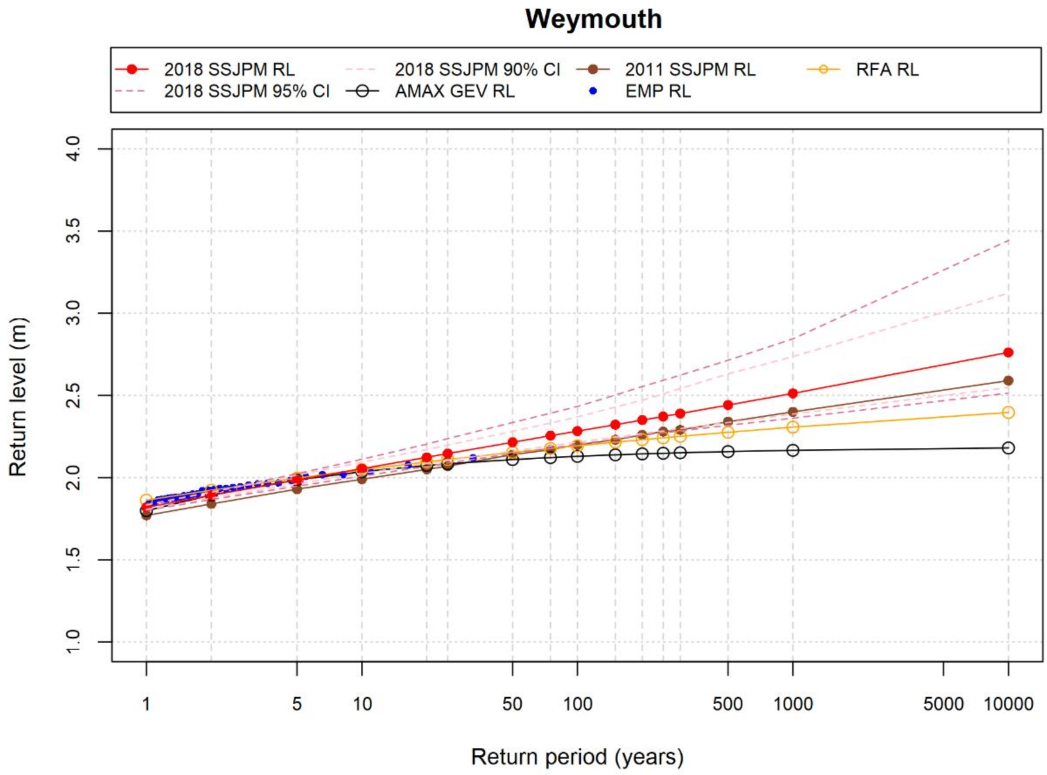


Figure F.48: Comparison at Weymouth tide gauge site

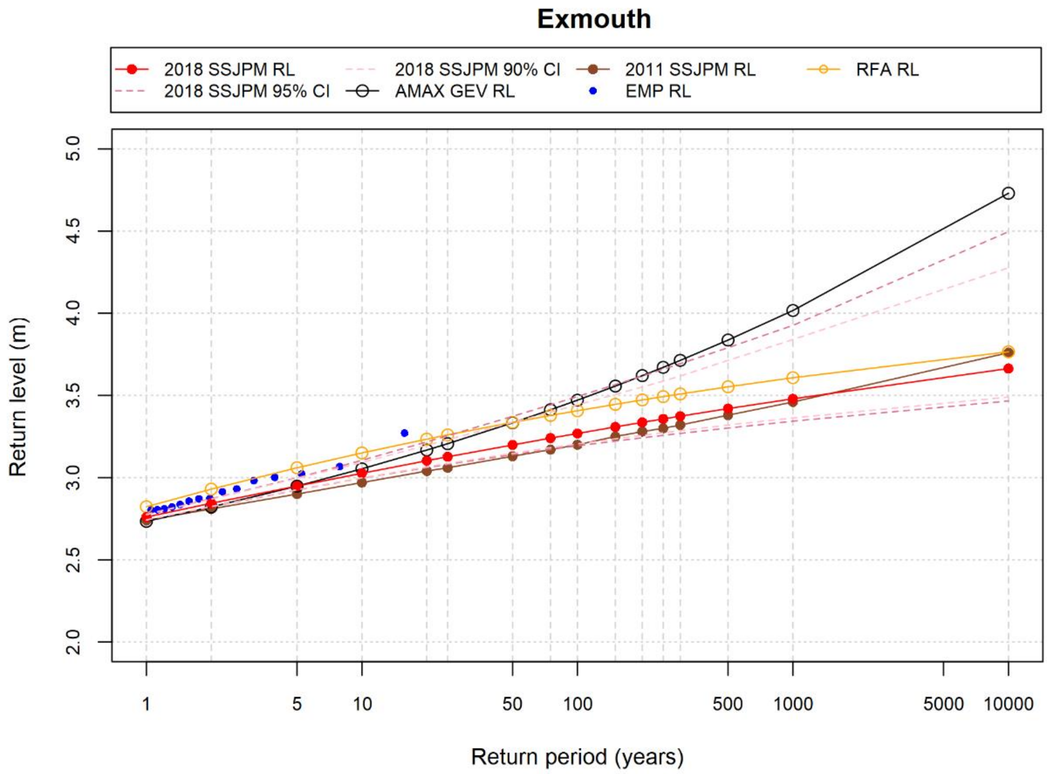


Figure F.49: Comparison at Exmouth tide gauge site

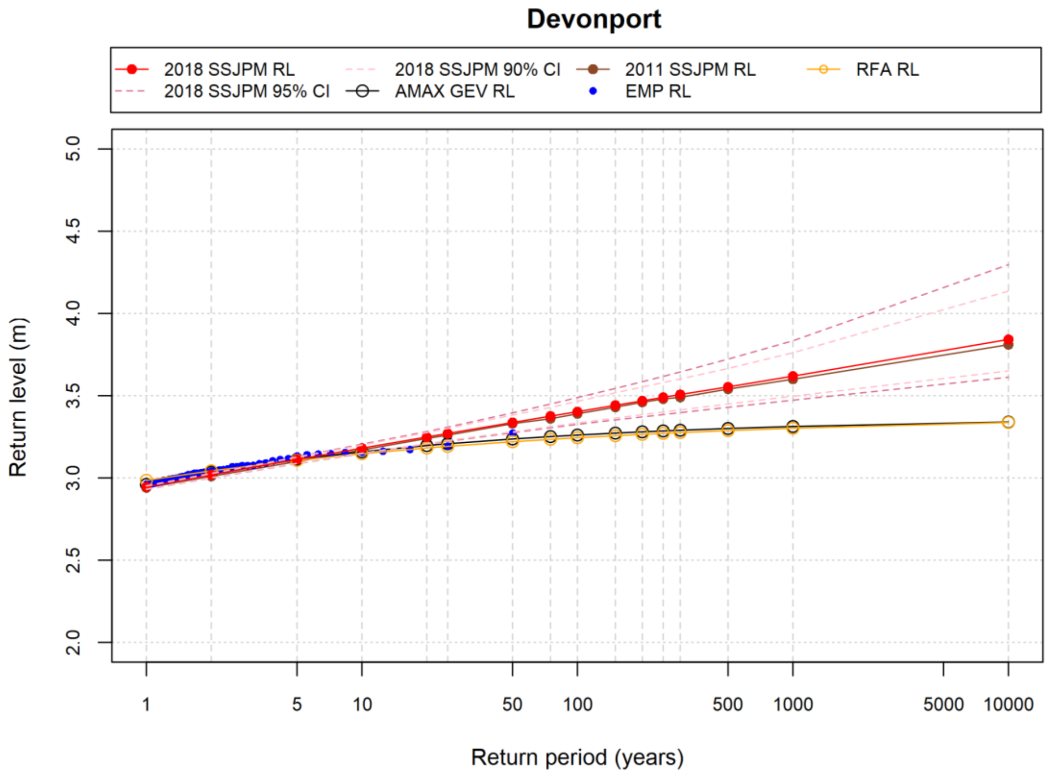


Figure F.50: Comparison at Devonport tide gauge site

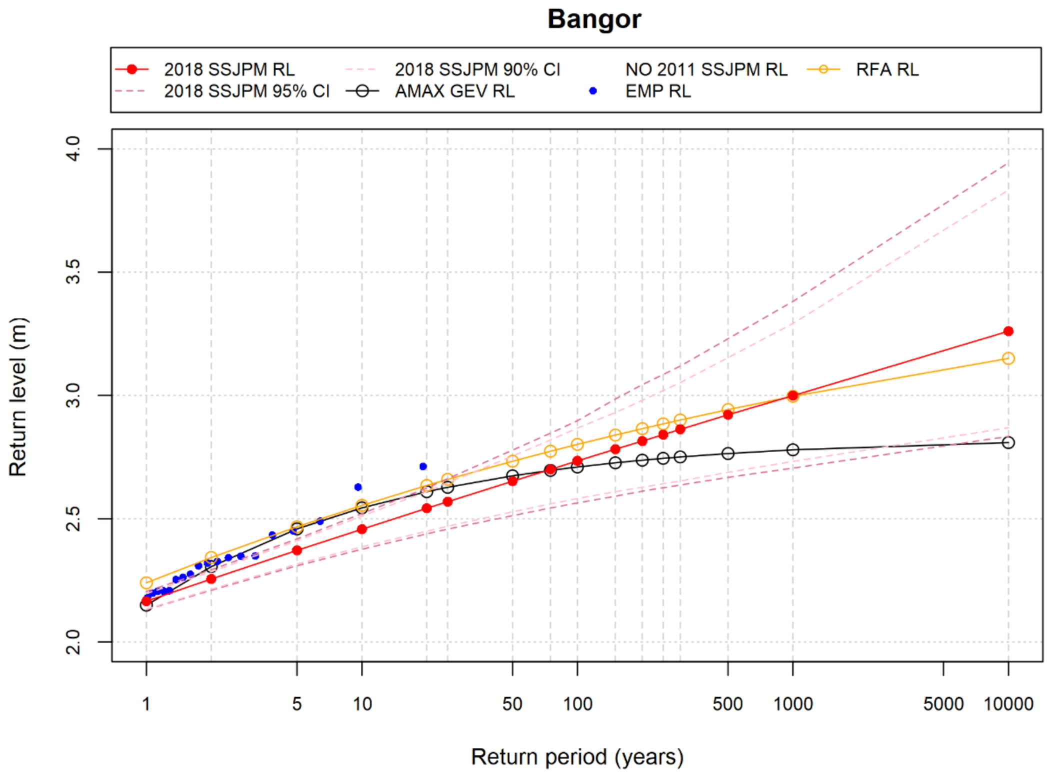


Figure F.51: Comparison at Bangor tide gauge site

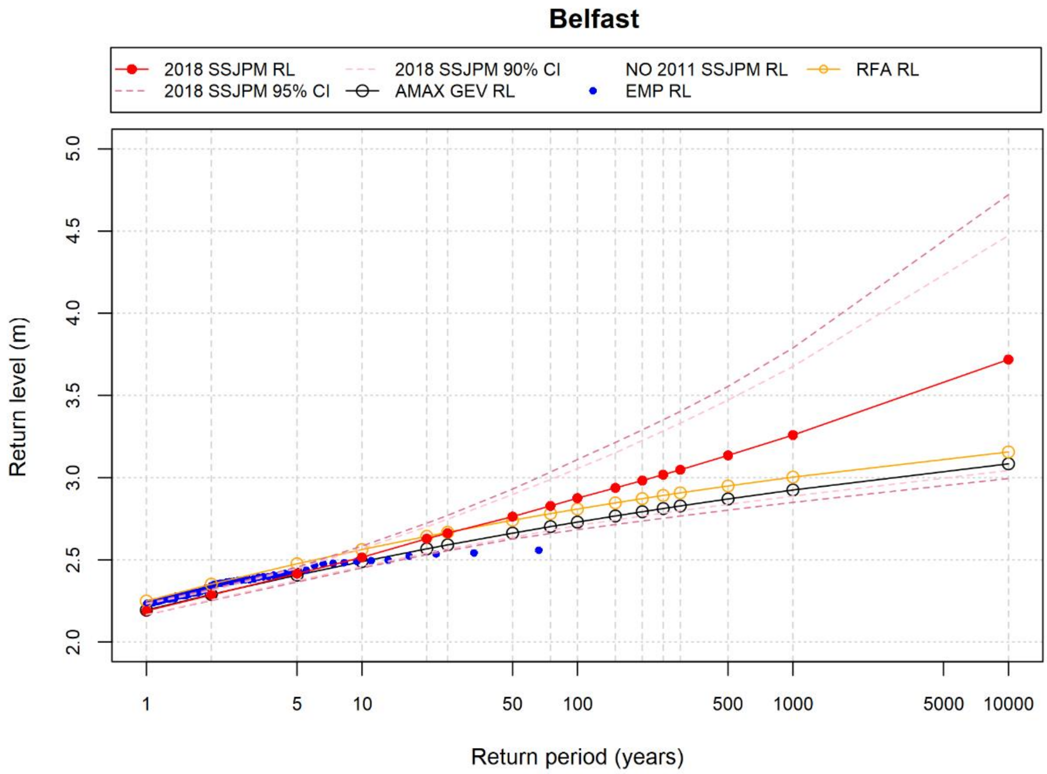


Figure F.52: Comparison at Belfast tide gauge site

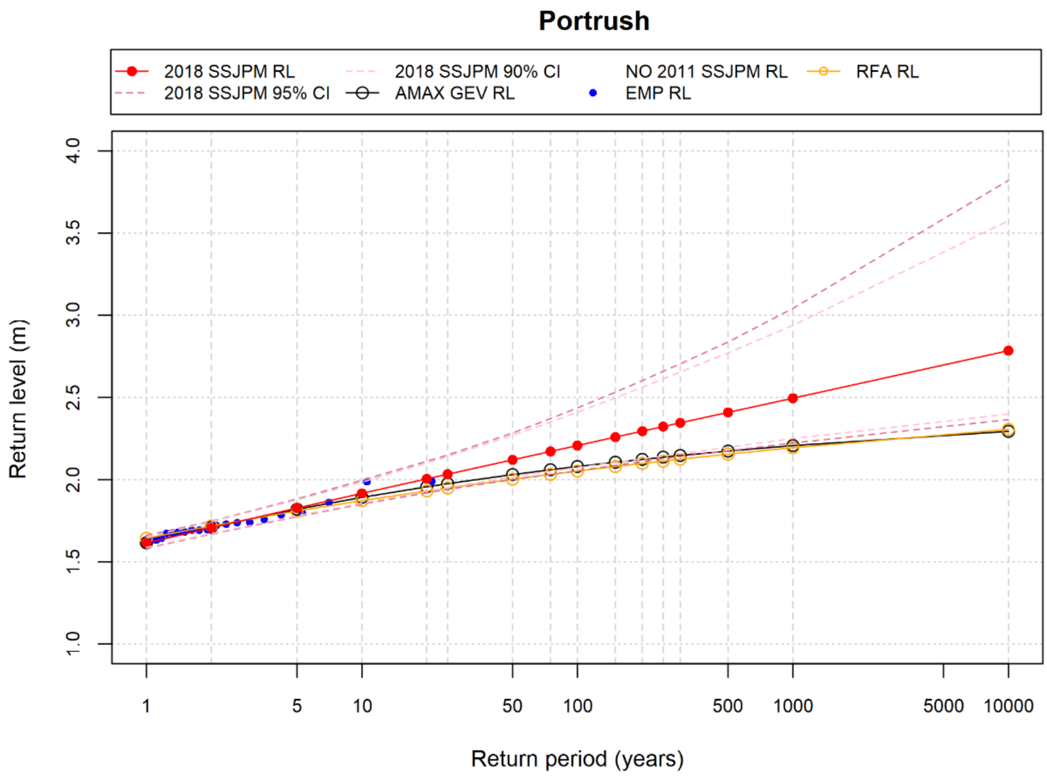


Figure F.53: Comparison at Portrush tide gauge site

Appendix G: Model validation

G.1.Comparison of SSJPM, empirical and GEV estimates of return levels

A useful means of validating the model is to compare the output of the SSJPM approach with other means of estimating return levels.

One simple approach is to estimate a return period empirically from the data. For example, if a level is exceeded 5 times in a 20-year record, then that level has a return period of 4 years. As a means of estimating return levels, this approach is restricted to return periods within the range of the data and is highly uncertain at longer return periods and when the data record is short. This approach is therefore not recommended as a valid approach for estimating return levels, but rather as a way of evaluating model fit. This can therefore be used to check whether the SSJPM is capturing the distributional properties of observed ESLs.

Alternatively, comparisons can be made with estimates obtained from fitting a model to AMAX data; this is typically represented as a generalised extreme value (GEV) distribution. The SSJPM results were compared with those from the GEV model as a sense check.

Return levels from the SSJPM, GEV and RFA approaches (outlined in Appendix E) were estimated at each tide gauge corresponding to return periods of 1, 2, 5, 10, 20, 25, 50, 75, 100, 150, 200, 250, 300, 500, 1,000 and 10,000 years. Return levels were also empirically estimated from the data and the comparisons are shown in Appendix F.

The return level curves in Appendix F show that the SSJPM gives comparable results to the GEV model, with the largest deviations occurring at long return periods. At long return periods, the SSJPM often gives a higher estimate of the return level compared with the GEV model. However, at the sites where the SSJPM gives a lower estimate (for example, Whitby), the estimate from the GEV model falls within the 95% confidence interval of the SSJPM estimate.

When compared with empirical estimates of the return level, the SSJPM generally captures ESL behaviour well. However, the quality of fit varies by tide gauge and by return period. Table G.1 summarises the quality of fit at each gauge, grouped into categories representing good, satisfactory and poor fits for low (1–5 years), medium (5–15 years) and long (15+ years) return periods. This has been determined by visual inspection of the plots in Appendix F. The scores highlighted in bold indicate cases where the SSJPM is not only a poor fit, but underestimates the probability of ESLs within that band. A striking example of this occurs at Lerwick, where the SSJPM consistently underestimates over all the return periods and the GEV model better represents the observed data (Figure F.28). There are also sites, such as Sheerness, where the SSJPM overestimates return levels with respect to the data (Figure F.43). This case represents less of an operational risk but should be investigated further.

Table G.1: Evaluation of model fit for low, medium and high return periods at each gauge based on comparison of SSJPM return levels with empirical estimates

Site	Low (1–5 years)	Medium (5–15 years)	High (15+ years)
Jersey	Satisfactory	Poor	Satisfactory
Newlyn	Good	Satisfactory	Satisfactory
St Mary's	Good	Satisfactory	Poor
Padstow	**Poor**	Poor	N/A
Ilfracombe	Good	Good	Good
Hinkley	Satisfactory	Good	Good
Avonmouth	Good	Satisfactory	Satisfactory
Newport	**Poor**	Poor	Satisfactory
Mumbles	Good	Satisfactory	Good
Milford Haven	Good	Poor	Good
Fishguard	Good	Good	Satisfactory
Barmouth	Good	Good	Good
Holyhead	Good	Good	Good
Llandudno	Good	**Poor**	Good
Hilbre	Good	Satisfactory	Satisfactory
Liverpool	Good	Satisfactory	Satisfactory
Isle of Man	Good	Satisfactory	**Poor**
Heysham	Satisfactory	Good	Satisfactory
Workington	Good	Satisfactory	Poor
Portpatrick	Good	Good	Satisfactory
Millport	Good	Good	Good
Islay Port Ellen	Good	Satisfactory	Good
Tobermory	Good	Good	Good
Ullapool	Good	Good	Good
Stornoway	Good	Good	Good
Kinlochbervie	Good	Satisfactory	Satisfactory
Lerwick	**Poor**	**Poor**	**Poor**
Wick	Good	Good	Good
Moray Firth	Good	Good	N/A
Clachnaharry	Good	Good	Good
Aberdeen	Good	Good	Satisfactory
Leith	Good	Good	Good
Grangemouth	Poor	Satisfactory	N/A
North Shields	Good	Satisfactory	Satisfactory
Whitby	Satisfactory	Poor	Poor
Immingham	Good	Good	Satisfactory
Cromer	Satisfactory	Good	Satisfactory

Site	Low (1–5 years)	Medium (5–15 years)	High (15+ years)
Lowestoft	Good	Good	Good
Felixstowe	Good	Good	Good
Harwich	Satisfactory	Satisfactory	Satisfactory
Southend	Good	Good	Good
Sheerness	Poor	Poor	Poor
Dover	Good	Satisfactory	Satisfactory
Newhaven	Good	Satisfactory	Good
Portsmouth	Good	Good	Good
Bournemouth	Good	Good	Good
Weymouth	Good	Good	Good
Exmouth	Satisfactory	Satisfactory	N/A
Devonport	Good	Good	Good
Belfast	Good	Good	Satisfactory
Bangor	**Poor**	Satisfactory	**Poor**
Portrush	Good	Good	Good

G.2.Regional frequency analysis

Standard approaches to extreme value modelling use information at a single site, whereas RFA methods use information from neighbouring sites in the estimation procedure.

Clusters of regions are defined pre-analysis in which sites are deemed statistically homogeneous up to a site-specific index, before the data at each site are standardised with respect to this index – typically an extreme value threshold in these applications. The data are pooled, before a regional GPD is fitted to the data pooled over the entire region, under the assumption that the shape parameter is constant over all sites. This method is particularly advantageous in scenarios where the data duration is short, as the pooling of data can reduce uncertainty in return level estimates. Since both approaches use some level of spatial information in the analysis, return levels estimated using the SSJPM approach and RFA were compared (see Appendix F).

The sites were clustered into homogeneous regions before the analysis using k-means clustering (see Figure G.1). Clustering was based on:

- the longitude and latitude of the sites to ensure that spatially adjacent sites were more likely to be grouped together
- the 99.9% quantile of the sea level distribution to ensure that sites with similar extremal behaviour were more likely to be grouped together

The number of clusters was selected using the ‘elbow method’ using the within-cluster sums of squares as a measure of cluster similarity.

Figure G.1: Sites assigned to 13 homogeneous regions using k-means clustering

Figure G.2 shows this criterion for up to 49 clusters in the data. The elbow method involves visually inspecting this figure to pick the number of clusters above which there are negligible drops in the within-cluster sum of squares. This is a subjective choice; Figure G.2 shows that 7–14 clusters would be a sensible solution. For the purpose of this analysis, a 13-cluster solution was chosen so that clusters were smaller and more localised effects were retained in the model. The chosen 13 clusters generally gave sensible results when compared with the SSJPM and GEV models. Sensitivity testing was carried out on the number of clusters that made negligible difference to return level estimates.

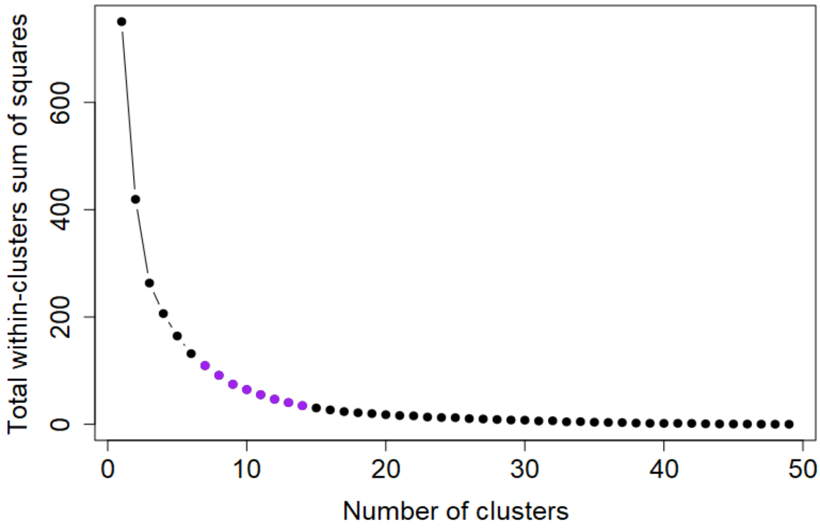


Figure G.2: Within-cluster sum of squares plotted against the number of clusters fitted using k-means

Notes: The purple dots represent plausible solutions and are used for testing sensitivity of the chosen 13-cluster solution.

An extreme value threshold was selected corresponding to the 99.9% quantile at all sites, which seemed sensible according to standard threshold diagnostics. A more comprehensive treatment could be used to account for the uncertainty regarding threshold selection, but for the purposes of validating the SSJPM, this value was fixed for the RFA approach.

The plots in Appendix F show that, in the majority of cases, the return levels estimated using the SSJPM are comparable with those estimated using RFA. In some cases, RFA appears to fit better to the data (for example, Lerwick; Figure F.28).

However, there are cases when RFA gives unrealistic levels at high return periods (for example, Dover; Figure F.44). In this instance, levels are heavily influenced by the largest event, which occurred on the east coast of England in December 2013, and skews the return level curve to implausible levels. The SSJPM is less sensitive to the influence of unusually large events; the 2013 event is estimated to have a return period of approximately 500 years under the SSJPM in contrast to 75 years under RFA.

G.3.Validation of SSJPM return periods using AMAX data

Using the SSJPM, each observation of the AMAX series is associated with a return period. This information was used to count the number of times in the observational record that a return period has been exceeded. This was compared with the expected number of exceedances based on the record length, which was modelled using a binomial distribution. This allowed:

- evaluation of whether the estimation of return periods was consistent with that observed in the AMAX series
- identification of any gauges where the model did not perform well

This analysis was conducted for each gauge for return periods corresponding to 1, 2, 5, 10, 20, 25, 50, 75, 100, 150, 200, 250, 300, 500, 1,000 and 10,000 years using the SSJPM and the GEV model. Gauges were grouped into good, satisfactory and poor performers based on how many estimated return periods exhibited more exceedances than expected. A summary of this analysis is shown in Tables G.2 to G.4 for good, satisfactory and poor performance respectively.

Table G.2: Good performing tide gauges based on median SSJPM return levels exhibiting more exceedances than expected at less than 2 return periods (determined using binomial counts)

Name	Record length (years)	Median return level range (m)	Number of return periods with more exceedances than expected					
			AMAX GEV	SSJPM median	SSJPM 2.5%Q	SSJPM 5%Q	SSJPM 95%Q	SSJPM 97.5%Q
Aberdeen	68	0.9	3	0	1	0	0	0
Avonmouth	40	1.9	2	1	1	1	1	1
Barmouth	25	1.6	2	0	1	1	0	0
Belfast	107	0.90	1	0	5	5	0	0
Bournemouth	18	0.9	1	1	1	1	0	0
Cromer	32	2	2	0	1	0	0	0
Devonport	56	0.9	1	0	2	2	0	0
Felixstowe	28	2.1	1	0	1	0	0	0
Fishguard	53	0.9	0	0	0	0	0	0
Harwich	30	1.8	1	1	1	1	0	0
Hilbre	32	1.3	2	1	1	2	1	1
Hinkley	26	1.5	2	1	2	2	0	0
Holyhead	46	1	3	1	3	3	0	0
Ilfracombe	42	1	2	0	0	0	0	0
Port Ellen	23	1.4	1	1	4	4	0	0
Jersey	25	1	1	0	0	0	0	0
Leith	29	1	3	0	1	1	0	0
Milford Haven	56	1.1	2	0	2	2	0	0
Moray Firth	11	0.9	1	0	1	1	0	0
Mumbles	24	1.5	1	0	1	1	0	0
Newhaven	50	1.1	3	0	4	2	0	0
Newlyn	102	0.8	2	0	0	0	0	0
North Shields	63	1.2	3	1	4	4	1	1
Padstow	20	0.9	0	0	1	1	0	0
Portbury	9	1.3	1	0	1	1	0	0
Portrush	22	1.2	1	0	4	4	0	0
Sheerness	50	1.9	1	0	0	0	0	0
St Mary's	32	0.7	2	0	0	0	0	0

Name	Record length (years)	Median return level range (m)	Number of return periods with more exceedances than expected					
			AMAX GEV	SSJPM median	SSJPM 2.5%Q	SSJPM 5%Q	SSJPM 95%Q	SSJPM 97.5%Q
Tobermory	27	1.5	1	1	1	1	0	0
Ullapool	47	1.1	4	0	2	2	0	0
Weymouth	36	0.9	2	0	3	1	0	0
Whitby	37	1.4	1	1	2	2	1	1
Wick	51	0.8	1	1	5	4	1	1

Table G.3: Satisfactory performing tide gauges based on median SSJPM return levels exhibiting more exceedances than expected at 2–4 return periods (determined using binomial counts)

Name	Record length (years)	Median return level range (m)	Number of return periods with more exceedances than expected					
			AMAX GEV	SSJPM median	SSJPM 2.5%Q	SSJPM 5%Q	SSJPM 95%Q	SSJPM 97.5%Q
Clachnaharry	27	1.23	1	2	3	3	1	1
Exmouth	18	0.90	2	2	4	4	1	1
Grangemouth	19	1.06	3	3	4	4	1	1
Heysham	52	1.77	2	2	2	2	0	0
Isle of Man	23	1.17	2	3	4	4	1	1
Llandudno	24	1.11	2	3	3	3	1	1
Millport	36	1.77	1	2	5	5	0	0
Newport	24	1.8	1	3	4	5	1	1
Portpatrick	49	1.27	3	2	6	5	1	1
Portsmouth	56	0.93	2	2	2	2	0	0
Southend	22	1.07	2	2	4	4	0	0
Stornoway	38	0.89	4	2	5	5	1	1
Workington	25	1.57	1	3	3	3	1	0

Table G.4: Poor performing tide gauges based on median SSJPM return levels exhibiting more exceedances than expected at more than 4 return periods (determined using binomial counts)

Name	Record length (years)	Median return level range (m)	Number of return periods with more exceedances than expected					
			AMAX GEV	SSJPM median	SSJPM 2.5%Q	SSJPM 5%Q	SSJPM 95%Q	SSJPM 97.5%Q
Bangor	23	1.1	2	4	6	6	3	3
Dover	67	1.59	3	4	6	6	1	1
Immingham	58	1.75	3	5	6	5	2	1
Kinlochbervie	25	1.29	2	4	4	4	1	1
Lerwick	58	0.6	1	7	8	9	6	6
Liverpool	27	1.75	3	4	5	5	0	0
Lowestoft	53	2.3	2	4	7	5	0	0

G.4.Summary of confidence in the SSJPM

Confidence in the SSJPM was assessed using a number of different criteria, which were used in the validation process. For each criterion, an assessment is made as to whether users should have high, medium or low confidence in the SSJPM. Again, this is subjective and depends on the opinion of the user. The criteria used for assessment were as follows.

- **AMAX GEV**. A visual comparison is made between the return level curves produced by the SSJPM and a GEV analysis of the annual maxima (AMAX approach). These are shown on the plots in Appendix F. Confidence is assessed based on the similarity between GEV and SSJPM levels at low return periods (<5 years). Return levels are not compared at high return periods as the GEV model tends to underestimate these levels (Dixon and Tawn 1999).
- **Empirical**. A visual comparison is made between the return levels estimated empirically from the data and the SSJPM return level curve. An assessment is made for low, medium and high return periods for each gauge based on how well the curve fits to the data (commonly used as a diagnostic of model fit). The overall assessment using this criterion is based on an average of the assessments in Section G.1 at each gauge.
- **Exceedance probabilities**. These assessments are taken from the analysis of exceedance probabilities found in Section G.3. ESLs corresponding to 16 different return periods are estimated.
  - A high confidence level is given if fewer than 2 of these return periods give more exceedances than expected.
  - A medium level is given if 2–4 return periods exhibit more exceedances than expected.
  - A low level is given if more than 4 return periods give more exceedances than expected.
- **RFA**. A visual comparison is made between the ESL return level curves from the SSJPM and an RFA approach. Like the AMAX GEV comparison, confidence is assessed based on comparison with levels at low return periods.
- **Uncertainty bounds**. A judgement is made about the confidence in the model based on the width of the 95% ESL return level confidence intervals from the SSJPM at high return periods. In general, a low level of confidence is given to widths >1.5m, a medium level is given to widths between 0.75m and 1.5m, and a high level is assigned to widths <0.75m. The width of the interval is also balanced with the length of the data series as, for example, an estimate of the 10,000-year return level from an analysis of 10 years of data is likely to be highly uncertain. This assessment is therefore perhaps prone to greater subjectivity.

Figure G.3 shows the assessments made at each tide gauge using the criteria described above. Examples of gauges that perform well across all criteria include Leith, Weymouth, Devonport and Holyhead. No gauge is assigned to the low level in all 5 criteria, but sites where the SSJPM performs poorly include Lerwick (4 low levels) and Sheerness (3 low levels).

An overall score representing the performance of the SSJPM is made using the assessments described above. For each individual criterion, values of 1, 2 and 3 are given to assessments of low, medium and high respectively. Weights are assigned to each criterion based on the importance in assessing model performance.

- Weights of 0.3 were assigned to empirical and uncertainty bounds.
- Weights of 0.15 were assigned to AMAX GEV and RFA.
- A weight of 0.1 was assigned to exceedance probabilities.

Note that these weights are highly subjective and may change depending on the user's opinion. The final scores are shown in Table G.5, where the gauges with the 5 lowest scores are highlighted.

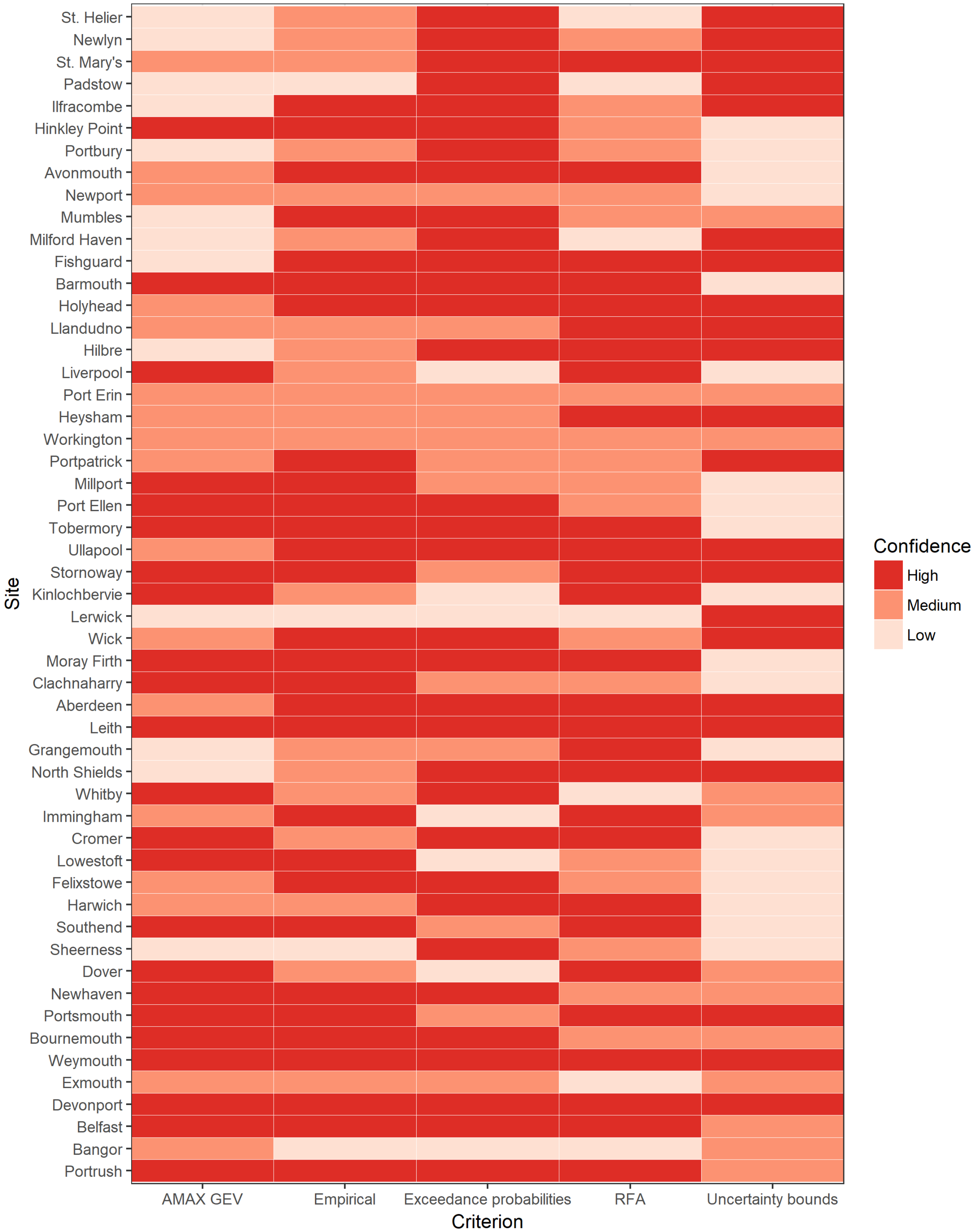


Figure G.3: Confidence in the SSJPM approach based on a range of validation criteria, grouped into high, medium and low confidences

Table G.5: Scores based on the overall performance of the SSJPM at each gauge

Site	Score		Site	Score
St Helier	2.1		Lerwick	1.6
Newlyn	2.25		Wick	2.7
St Mary's	2.55		Moray Firth	2.4
Padstow	1.8		Clachnaharry	2.15
Ilfracombe	2.55		Aberdeen	2.85
Hinkley Point	2.25		Leith	3
Portbury	1.65		Grangemouth	1.7
Avonmouth	2.25		North Shields	2.4
Newport	1.7		Whitby	2.1
Mumbles	2.25		Immingham	2.35
Milford Haven	2.1		Cromer	2.1
Fishguard	2.7		Lowestoft	2.05
Barmouth	2.4		Felixstowe	2.1
Holyhead	2.85		Harwich	1.95
Llandudno	2.45		Southend	2.3
Hilbre	2.4		Sheerness	1.35
Liverpool	1.9		Dover	2.2
Port Erin	2		Newhaven	2.55
Heysham	2.45		Portsmouth	2.9
Workington	2		Bournemouth	2.55
Portpatrick	2.6		Weymouth	3
Millport	2.15		Exmouth	1.85
Port Ellen	2.25		Devonport	3
Tobermory	2.4		Belfast	2.7
Ullapool	2.85		Bangor	1.45
Stornoway	2.9		Portrush	2.7
Kinlochbervie	1.9			

Notes: The gauges with the 5 lowest scores are highlighted in green.

Appendix H: ESLs at upstream gauges

This appendix describes the levels derived at 3 gauges located in Welsh estuaries and one gauge in a Northern Ireland sea lough. Appendix B.2.2 details the data availability at these gauges. As discussed in Section 3.7, levels at these gauges are derived by comparing observed quantiles between sea levels at the upstream gauges with a neighbouring gauge for which levels were derived using the SSJPM. These levels are shown in Table H.1 for return periods of 1, 2, 5 10, 20, 25, 50, 75, 100, 150, 200, 250, 300, 500, 1,000 and 10,000 years. Levels are correct to base year 2017.

Table H.1: ESLs (in mOD) derived at upstream gauges by quantile comparison

Upstream gauge	ESL site used	Return period (years)								
		1	**2**	**5**	**10**	**20**	**25**	**50**	**75**	100
Llanelli	Mumbles	5.18	5.29	5.44	5.55	5.66	5.69	5.80	5.86	5.91
Pontycob	Mumbles	5.52	5.60	5.70	5.77	5.85	5.87	5.95	5.99	6.02
Tintern	Newport	8.45	8.64	8.90	9.09	9.29	9.36	9.57	9.70	9.80
Victoria Lock	Port Erin	2.95	3.03	3.14	3.22	3.30	3.32	3.40	3.45	3.48

Upstream gauge	ESL site used	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Llanelli	Mumbles	5.97	6.02	6.05	6.08	6.16	6.27	6.67
Pontycob	Mumbles	6.07	6.10	6.12	6.14	6.20	6.28	6.55
Tintern	Newport	9.94	10.04	10.12	10.18	10.37	10.65	11.69
Victoria Lock	Port Erin	3.52	3.55	3.58	3.60	3.65	3.73	3.98

This approach involved fitting a linear model to quantiles of sea level corresponding to equally spaced probabilities above 95% at the upstream gauge and the selected neighbouring gauge. The SSJPM return levels at the neighbouring gauge are used to predict the return levels at the upstream gauge using this model. Two examples of this are shown in Figure H.1 for Victoria Lock in Northern Ireland and Llanelli in Wales. In both cases, the linear model captures well the relationship between high quantiles at the 2 gauges.

The levels produced using this method are, however, associated with high uncertainty. For this reason, modelled levels have been used instead for level-to-level analysis of gauge data where available (for example, at Chepstow Bridge in Wales).

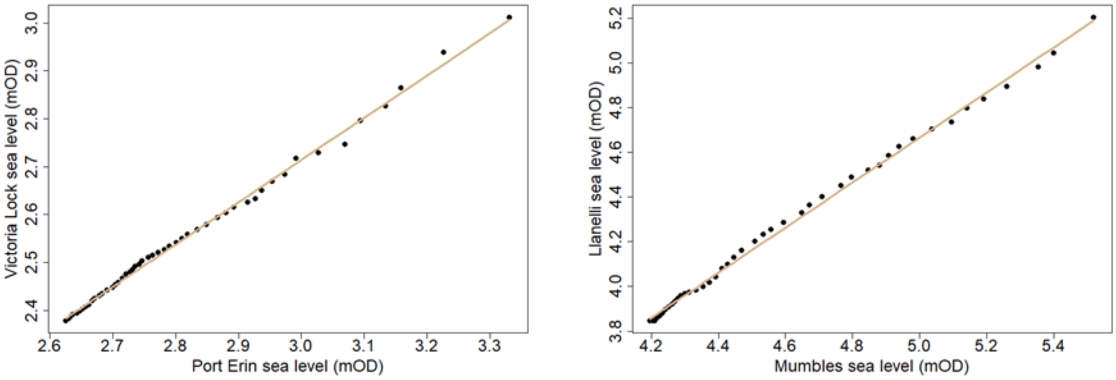


Figure H.1: Quantile comparison and line of best fit between Victoria Lock and Port Erin (left) and Llanelli and Mumbles (right)

Appendix I: Surge

I.1.Introduction

In addition to estimates of peak ESLs, practitioners require design tidal graphs for a range of applications including:

- tidal boundaries for hydrodynamic and sediment transport models
- still water inputs for wave overtopping analysis
- input data for flood forecasting procedures

A design tidal graph is a time series that quantifies how sea levels are expected to change through time during an extreme event. Figure I.1 shows an example design tidal graph.

This appendix details how design surge shapes have been derived based on an analysis of recorded data from the UK NTGN.

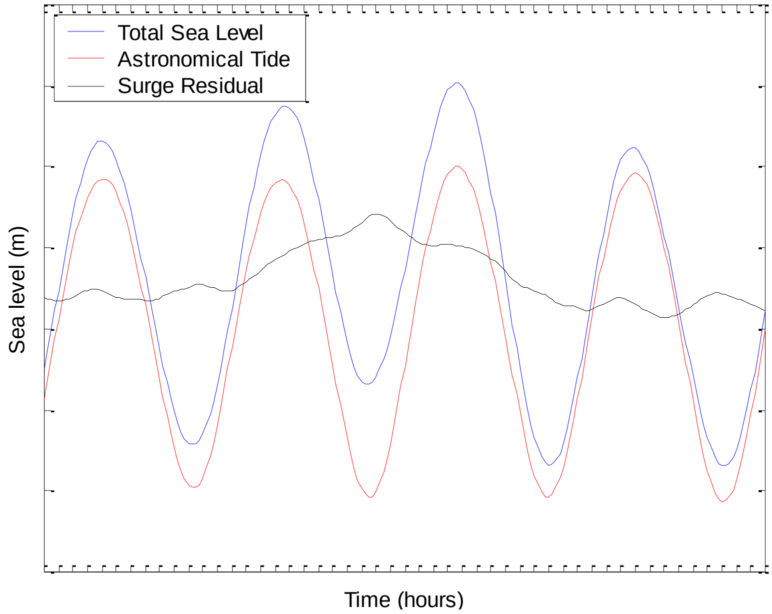


Figure I.1: Example design tidal graph illustrating surge residual

Notes: The red line represents the underlying astronomical tide (referred to hereafter as ‘tide’). The black line represents the progression of a storm surge (quantified here by surge residual). The blue line represents the observed or total sea level (referred to hereafter as ‘total sea level’). This is principally the combination of the tide and the storm surge, but may also include wind set-up.

I.2.Development of design surge shapes

The most important component of a design tidal graph is the design surge shape. Design surge shapes were generated as part of this study to provide a straightforward and consistent source of surge curves for practitioners. This section outlines the analytical work undertaken to generate the design surges.

I.2.1.Surge residual versus skew surge

As discussed in Section 3.2, surges can be defined numerically in 2 ways:

- surge residual (Figure I.1)

- skew surge (Figure I.2)[5]

Many practitioners have developed design surge shapes in the past using the variable surge residual, which is easily accessible from many tide gauge records.

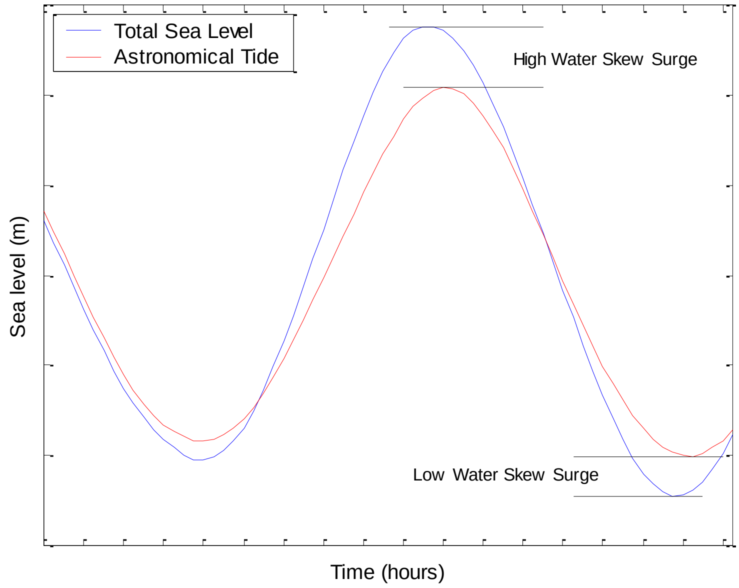


Figure I.2: Example design tidal graph illustrating skew surge

Surge residual values are not necessarily a reflection of true tidal surge but can arise fully, or in part, due to phase differences (that is, timing differences) between the predicted and observed tide. The differences can occur due to complex shallow flow processes referred to as tide-surge interaction. The phase difference gives an 'illusory' surge residual (Figure I.3).

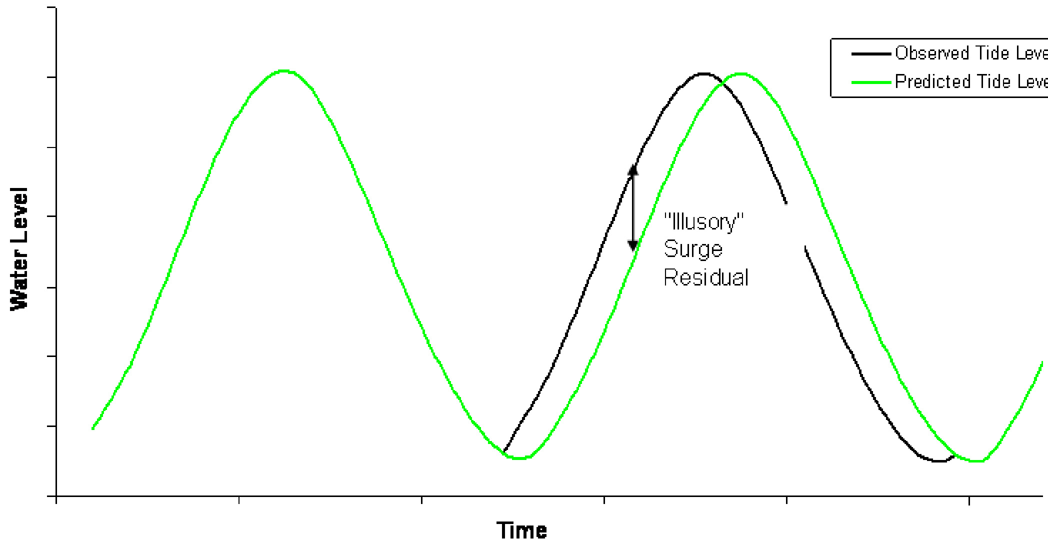


Figure I.3: Illusory surge residual

[5] The parameter 'surge residual' is equal to the observed sea level minus the predicted astronomical tidal level at a particular point in time. The parameter 'skew surge' refers to the difference between the maximum recorded sea level during a tidal cycle and the predicted maximum tidal level for that cycle, irrespective of their timing.

This ‘illusory’ surge is often most apparent at the mid-tide stage, where the change in level with time is at its greatest. Any phase difference will therefore inevitably give the most pronounced surge residual. An example is shown in Figure I.4.

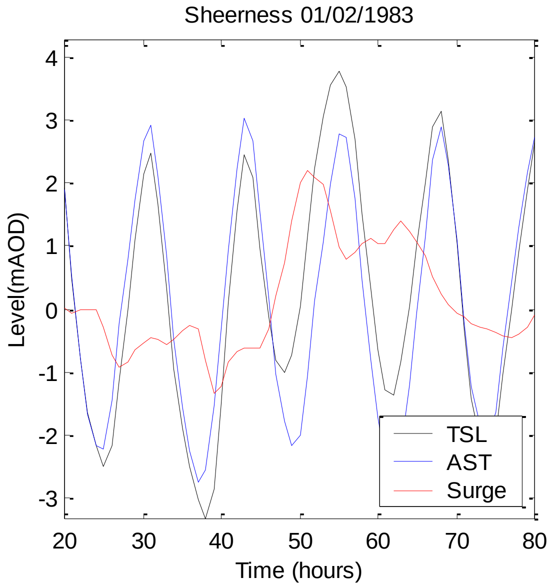


Figure I.4: Example of tendency for surge residual profiles to peak at mid-tide

Notes: AST = astronomical tide; TSL = total sea level

Since the use of surge residual data in the derivation of design surge shapes is complicated by timing issues, skew surge is preferred for analytical purposes. The use of skew surge removes all phase differences between predicted and observed tidal data.

To avoid the issues associated with surge residual data, the variable ‘skew surge’ was adopted in Environment Agency (2011) and updated for this study for the generation of design surges. Figure I.5 illustrates that, unlike surge residuals, there is no noticeable correlation between the magnitude of skew surge and the magnitude of tide level for Newlyn. This lack of correlation is also apparent for other tide gauge sites used in this study. This is also demonstrated in Williams et al. (2016).

The practical importance of this independence is that complicated timing issues do not need to be accounted for in the design of a tidal graph when the design surge shape is based on the variable skew surge. The only UK NTGN gauge site showing slight correlation between skew surge and tide level is at Sheerness (see Section I.2.2).

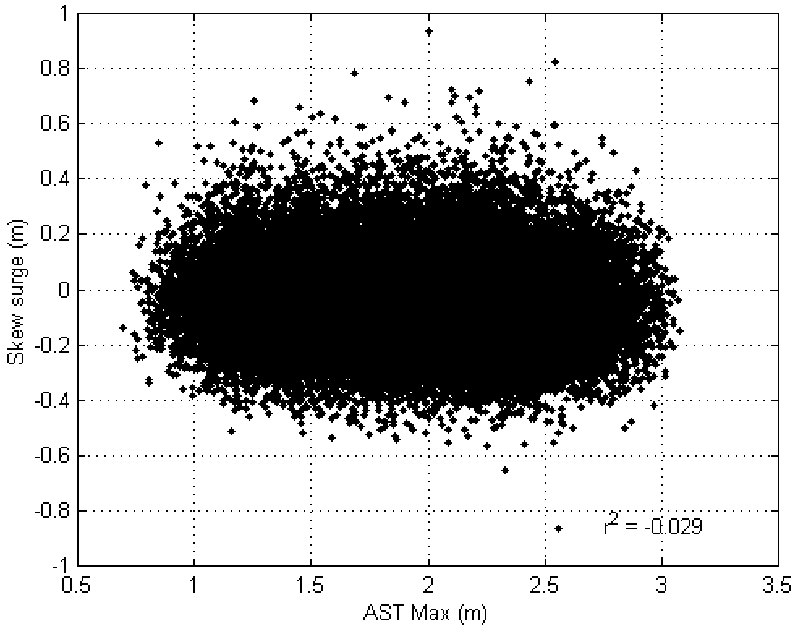


Figure I.5: Skew surge magnitude versus peak tide level (AST max) at Newlyn

Notes: AST = astronomical tide

I.2.2.Dependence at Sheerness

There is a lack of correlation between skew surge magnitude and peak tide magnitude at all gauge sites in this study except for Sheerness, which shows a slight bias towards extreme skew surges at neap peak tides (Figure I.6). The reason for this apparent dependence is not fully known and was not investigated in detail for this study. It could be the result of very large tide-surge interaction. Another possibility is systematic tidal prediction errors at the gauge; tidal predictions are less accurate in estuarine regions. As the calculation of skew surge is a product of total sea level and peak tide level, consistently overpredicted high tides would result in consistently lower skew surge to achieve the same recorded total sea level. Further investigation is required to determine whether this is the case at Sheerness.

The result of this apparent dependence is that the return levels may be overestimated at Sheerness. It was decided that these would be taken as a reasonable but conservative estimate of risk for this study.

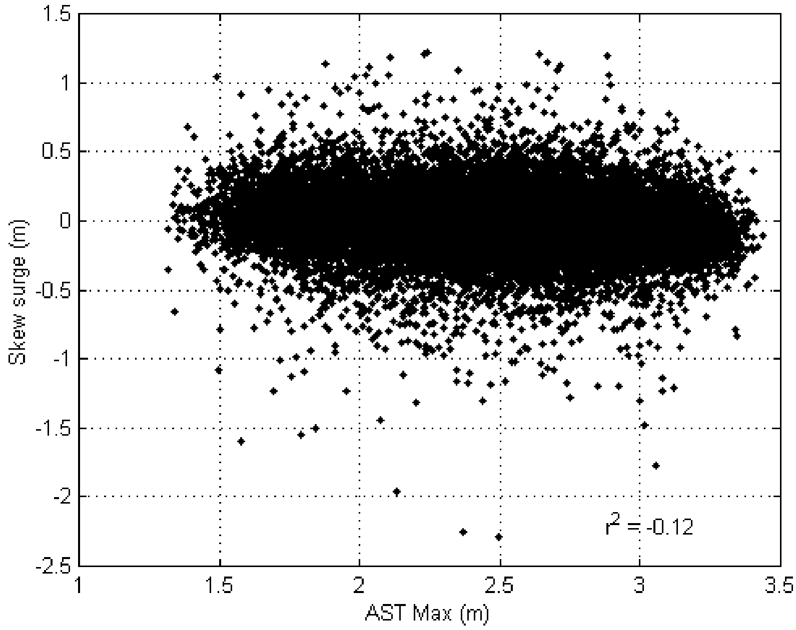


Figure I.6: Skew surge magnitude versus peak tide level (AST max) at Sheerness

Notes: AST = astronomical tide

I.2.3.Design surge shapes

The skew surge-based design surge profiles derived for this study were constructed using observed (total sea level) and predicted (tide) sea level data for UK NTGN sites in England, Wales and Scotland. From these data, the 15 largest surge events recorded at each gauge site were extracted. This involved extracting the high water skew surge value for each tide in a storm event and the low water skew surge value for each tide in a storm event (Figure I.2). To interpolate these values to a higher temporal frequency (15 minute), a number of interpolation schemes were implemented.

Figure I.7 shows examples of the surges extracted and interpolated for Aberdeen and Newhaven. These plots and others for the UK illustrate that skew surge profiles typically have one large surge peak, lasting between 40 and 90 hours, and in some cases secondary peaks before and/or after the principal peak. In almost all cases and sites in the UK, the surge profiles also exhibit a fair amount of more random, low magnitude (<0.40mOD) noise, before and after the primary peak. Because each of the events illustrated in Figure I.7 has a different peak magnitude, the similarity in the profile shapes is somewhat masked.

In Figure I.8, each of the 15 largest events for the same 2 sites is normalised to a peak value of 1, which helps to illustrate the similarity in form of the different surge profiles. In these normalised plots, the variations in the bottom 30% have been removed for clarity.

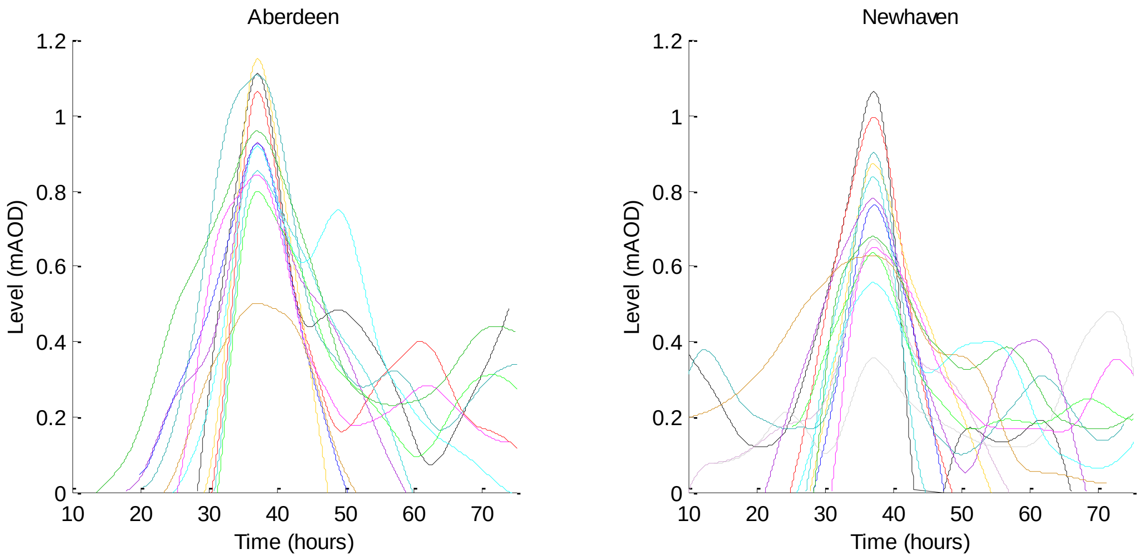


Figure I.7: Example of large surges profiles for 2 UK sites

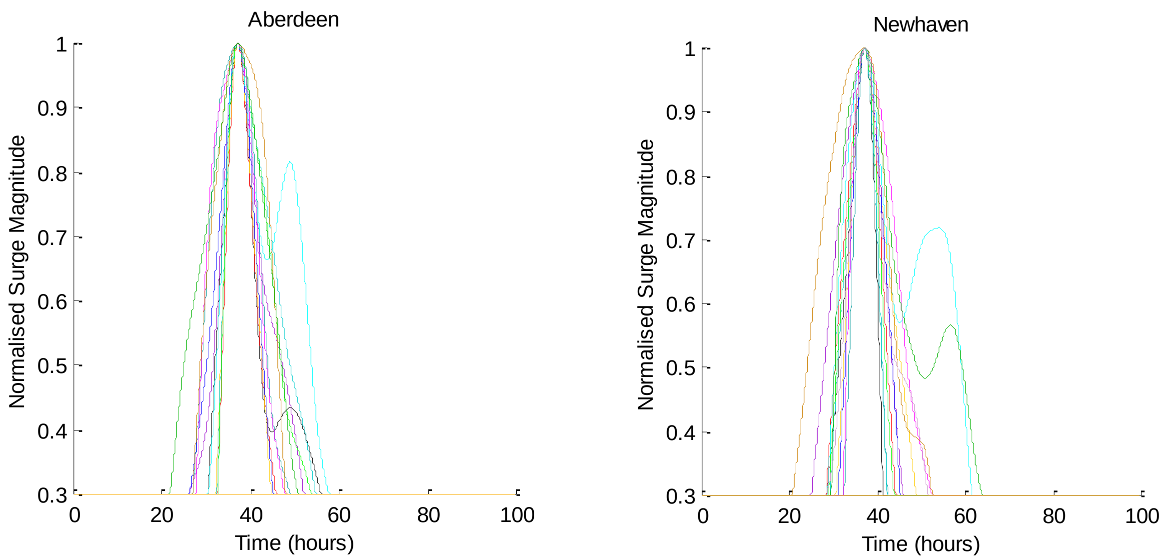


Figure I.8: Example of large surges profiles normalised for 2 UK sites to a value of 1

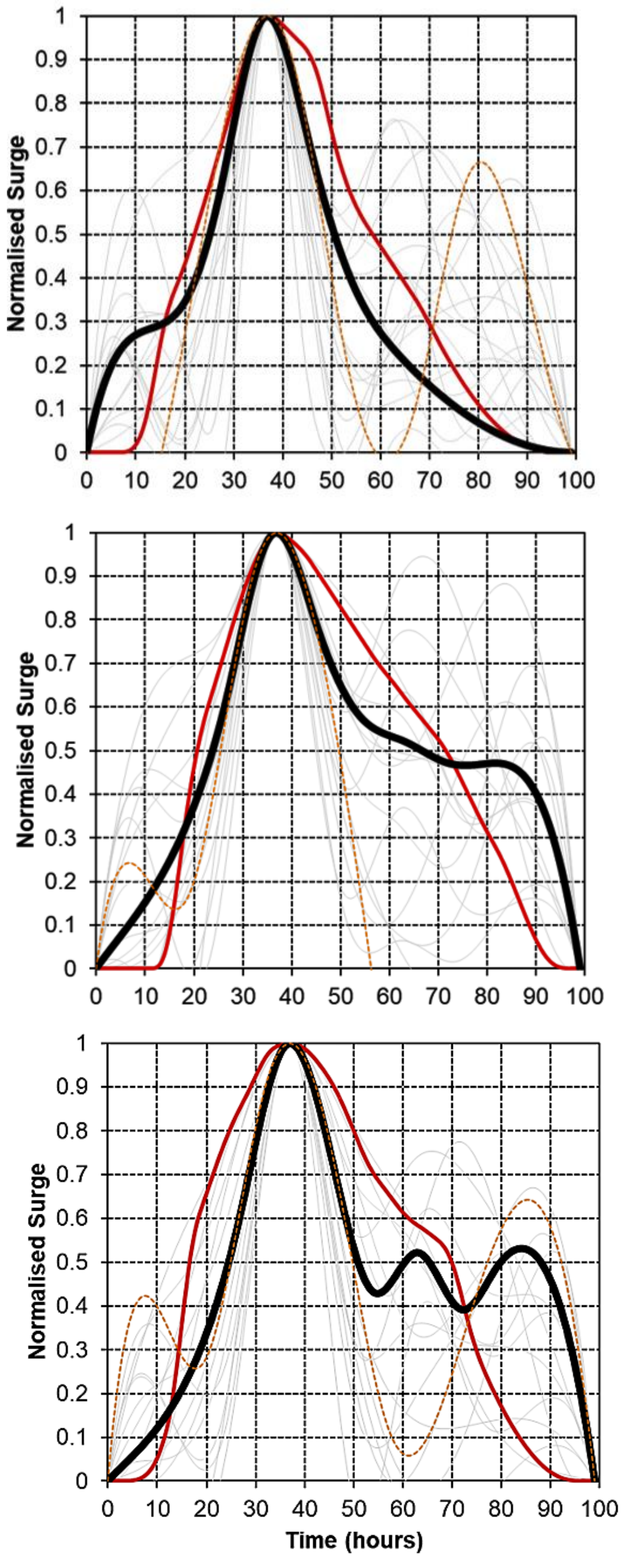
While the form of the surge profiles shown in Figure I.7 and Figure I.8 are clearly similar, there is also diversity. Consequently, deriving one design surge shape to represent an area for modelling purposes requires some form of generalisation. It is important that the generalised surge shape adopted for a site conforms with observations to ensure that it is a realistic representation of local processes. However, it must also be suitably conservative given that what is of interest is the extreme.

A number of numerical treatments of the surge data extracted and interpolated for each site were undertaken for Environment Agency (2011) to derive potential design surge shapes. A 'time-integrated duration surge' was adopted for the study. To generate this type of surge, first the duration of each of the 15 surges (excluding outliers) at particular levels in the surge column (that is, 10% level, 20% level and so on) was calculated. The maximum duration at each level in the surge column was then determined. These maximum durations were arranged to form the surge shape by determining the relative proportions of the duration expected on the rising and falling limbs of the surge. The surge shape was then smoothed. These 'time-integrated duration surges' were adopted on the premise that they provided the best representation of the largest surges – in terms of both shape and duration.

Since the publication of Environment Agency (2011), a number of large storm surge events have occurred around the UK coastline. The most notable of these was the event that occurred along the East Coast on 5 and 6 December 2013. At some gauge locations, the surge produced ESLs with a predicted return period in excess of between 1 in 100 years. This was largely due to the extreme storm surge. Thus, the surge profile for this event well represents an extreme scenario which could be expected with future ESLs. Comparison with this and other large surge events provides a useful indication of whether the design surge profiles derived for Environment Agency (2011) are representative of an extreme surge event.

Figure I.9 and Figure I.10 show comparisons of the surge profile developed for Environment Agency (2011) with the surge profiles derived from recorded gauge data during the events on 4 February 2014 and 5 December 2013 respectively. Surge at gauge sites where these events were significant and where gauge data were available are shown. All levels were interpolated to 15-minute intervals for comparison. The comparisons show that the event profiles are consistently narrower than the design profiles developed for Environment Agency (2011). This suggests the wider surge profiles are related to smaller surge events.

For this study, the design surge profiles were regenerated to more closely match the recent large event surge profiles. At each gauge site, the largest 15 surges were normalised and interpolated to consistent time intervals as performed previously for Environment Agency (2011). Suitable interpolation methods were tested to provide the best interpolation at each site. These profiles are shown in grey in Figures I.9 and I.10. For each time-step in the surge profile, outliers were removed before various percentiles of the remaining values were tested to find a representative profile. A value of 75% was chosen as this best matched the large recorded surge events of 2013 and 2014 while generally remaining wider and therefore more conservative. Initially, this process was carried out using time-steps of 15 minutes as with Environment Agency (2011), but this resulted in an unrealistic 'bumpy' profile. The process was instead carried out using interpolation to 4-hourly intervals and later interpolated to 15 minutes to achieve a smooth profile. The new 2018 design surge profiles developed by this method are shown in black in Figures I.9 and I.10.



(a)

(b)

(c)

Figure I.9: Surge profile comparison for (a) Weymouth, (b) Devonport and (c) Newlyn

Notes: Black line is the updated CFB 2018 profile, red line is the previous Environment Agency (2011) profile, grey is the interpolated largest 15 profiles and orange is the recorded 4th February 2014 event profile (interpolated to 15 minutes).

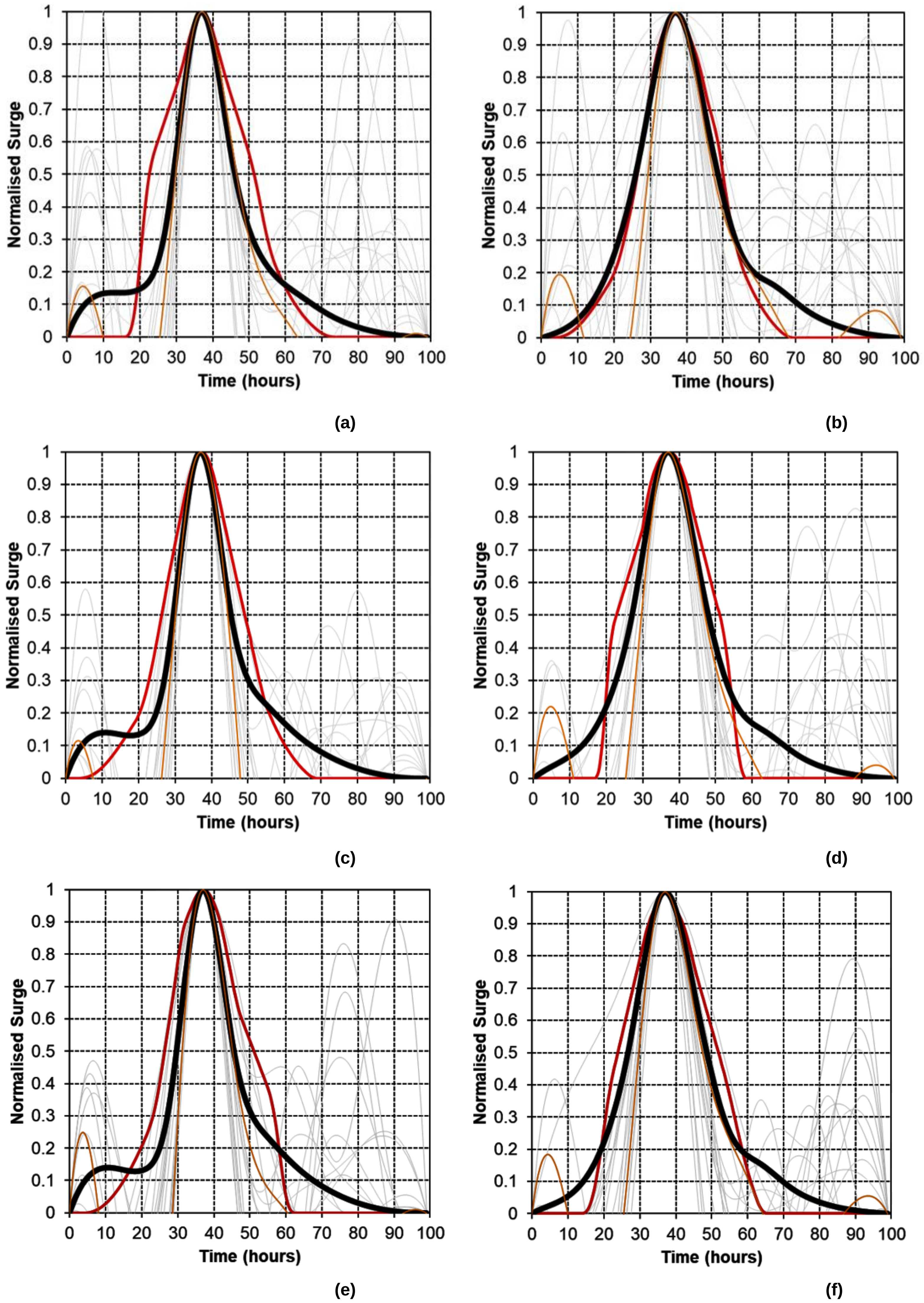


Figure I.10: Surge profile comparison for (a) North Shields, (b) Whitby, (c) Immingham, (d) Lowestoft, (e) Sheerness and (f) Dover

Notes: Black line is the updated CFB 2018 profile, red is the previous Environment Agency (2011) profile, grey is the interpolated largest 15 profiles and orange is the recorded 5–6 December 2013 event profile (interpolated to 15 minutes).

I.2.4.Where to apply the design surge shapes

There is some evidence of similarity of form in the final design surge shapes shown in Figure I.10 from a geographical perspective, but this similarity is only marginal. For practical purposes, it is necessary to assign the final design curves to act as donor surge shapes for geographical regions. Practitioners can then easily choose a surge shape to use in the derivation of a design tidal graph, even if the site of interest is not directly coincident with a UK NTGN site.

Table I.1 provides guidance on where the donor surge shapes should be applied geographically. It is important to note that:

- the assignment of these geographical regions is fairly arbitrary
- some sensitivity testing using different shapes may be appropriate for sites at the margins of the geographical sectors if the detail of the projects warrants this

Table I.1: Where to apply the donor surge shapes

Surge profile	Donor site	Apply from (clockwise around UK):
1	Wick	John o' Groats to Brora
2	Moray Firth	Brora to Lossiemouth (Moray Firth) – ceased operation
3	Aberdeen	Lossiemouth to Arbroath
4	Leith	Arbroath to North Berwick (Firth of Forth and Tay)
5	North Shields	North Berwick to Redcar
6	Whitby	Redcar to Spurn Head
7	Immingham	Spurn Head to Holme-next-the-Sea
8	Cromer	Holme-next-the-Sea to Winterton-on-Sea
9	Lowestoft	Winterton-on-Sea to Aldeburgh
10	Felixstowe	Aldeburgh to Walton-on-the-Naze
11	Sheerness	Walton-on-the-Naze to Margate (Thames Estuary)
12	Dover	Margate to Selsey
13	Portsmouth	Selsey to Milford-on-Sea (Solent and Isle of Wight)
14	Bournemouth	Milford-on-Sea to Swanage
15	Weymouth	Swanage to Salcombe
16	Devonport	Salcombe to Lizard Point
17	Newlyn	Lizard Point to Hartland Point (Titchberry)
18	St Mary's	Isles of Scilly
19	Ilfracombe	Hartland Point to Minehead
20	Hinkley Point	Minehead to Weston-super-Mare
21	Avonmouth	Weston-super-Mare to Caldicot (Severn)
22	Newport	Caldicot to Llantwit Major
23	Mumbles	Llantwit Major to Tenby
24	Milford Haven	Tenby to St David's Head
25	Fishguard	St David's Head to New Quay (Ceinewydd)
26	Barmouth	New Quay (Ceinewydd) to Aberderon Bay
27	Holyhead	Aberderon Bay to Amlwch

Surge profile	Donor site	Apply from (clockwise around UK):
28	Llandudno	Amlwch to Point of Ayr
29	Liverpool	Point of Ayr to Fleetwood
30	Heysham	Fleetwood to Haverigg Point (Morecambe Bay, Duddon Estuary)
31	Workington	Haverigg Point to Isle of Withorn (Solway Firth, Wigtown Bay)
32	Port Erin	Isle of Man, Ballyhalbert to Warrenpoint (Northern Ireland)
33	Portpatrick	Isle of Withorn to Girvan
34	Millport	Girvan to Mull of Kintyre (incl. Arran)
35	Port Ellen	Mull of Kintyre to Oban (including Islay, Jura, Colonsay)
36	Tobermory	Oban to Kyle of Lochalsh (including Tiree, Coll, Mull, Rhum, Eigg and Skye)
37	Ullapool	Kyle of Lochalsh to Point of Stoer
38	Kinlochbervie	Point of Stoer to John o’ Groats
39	Stornoway	Outer Hebrides
40	Lerwick	Orkney Islands, Shetland Islands
41	St Helier	Jersey
42	Bangor	Ballycastle to Ballyhalbert
43	Portrush	Londonderry to Ballycastle

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