Coastal flood boundary conditions for the UK: update 2018

User guide

SC060064/TR7

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Executive summary

Successful risk-based flood and coastal erosion risk management requires the best available information on coastal extremes. This best practice guidance updates and replaces advice given in 'Coastal Flood Boundary Conditions for UK Mainland and Islands. Design Sea Levels' published in 2011.

Work was carried out in 2017 to 2018 to develop and apply improved methods to update coastal extreme sea levels using a longer data record. The locations for which extreme sea levels are provided were also extended to include Northern Ireland and some estuary locations.

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

This user guide outlines the various outputs from the work and describes the method used to update the extreme sea levels. It provides practical guidance on how to choose an extreme sea level and to generate a design tidal curve for a particular coastal site. The guide ends with a worked example which uses Clovelly on the north Cornwall coast to illustrate the recommended stepwise approach.

The technical report accompanying this user guide provides more information, including details of the additional data and the improved scientific methods used in the update.

Detailed results from the update are given in a series of geographical information system (GIS) shapefiles available on data.gov.uk.

Contents

1. Introduction

Successful risk-based flood and coastal erosion risk management requires the best available information on coastal extremes. This best practice guidance updates and replaces advice given in 'Coastal Flood Boundary Conditions for UK Mainland and Islands. Design Sea Levels' (project SC060064) (Environment Agency 2011).

This project was carried out to develop and apply improved methods to update coastal extreme sea levels using a longer data record. Work was carried out in 2017 to 2018 using newly available data and incorporating scientific improvements. The locations for which extreme sea levels are provided were also extended to include Northern Ireland and some estuary locations.

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

This user guide provides practical guidance on how to view the findings of the extreme sea level and storm tide curve studies. It also explains how to use the results and includes a worked example. The technical report provides more information, including details of the additional data and the improved scientific methods used in the update. Detailed results are given in geographical information system (GIS) shapefiles available on https://environment.data.gov.uk/.

This update was carried out for the UK Coastal Flood Forecasting partnership, which includes the Environment Agency, Scottish Environment Protection Agency, Natural Resources Wales and the Department for Infrastructure Northern Ireland. 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. The project also included extensive consultation and wider involvement with UK practitioners and subject matter experts.

2. Coverage

The study has produced extreme sea levels for a continuous chainage of points around England, Scotland, Wales and Northern Ireland. The location of these points is shown in a series of maps in the appendix at the end of this report.

Additional chainages have been produced for:

- Firth of Clyde Islands
- Hebrides, Orkney and Shetland Islands
- Anglesey
- Isle of Wight

Additional points have been included for:

- St Mary's (Isles of Scilly)
- Port Erin (Isle of Man)
- St Helier (Jersey)

Inland extreme sea levels, which were not included previously, were produced for this update for many estuaries, harbours, loughs, lochs and tidal rivers.

This user guide also offers advice on the appropriate storm surge curves to use and details of where to apply them.

3. Summary of outputs

The main outputs from the project can 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, where these data are available
- Peak sea level values (that is, the maximum water levels recorded during a storm event) 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 is given on how to generate appropriate total storm tide curves for use with the extreme sea levels. These are the time series of sea levels expected during an extreme event. Standard surge profile shapes are provided for each part of the coast. These should be combined with an astronomical tide to give the total storm tide curve.
- Extension of the dataset in several key estuaries. A shapefile (CFB_Estuary_Boundaries_2018.shp) available on data.gov.uk allows users to determine the limits of where the open coastal levels can be applied in estuaries where estuary extreme sea levels are not provided.

3.1. Notes

– Note 1: Extreme sea levels are considered accurate to one decimal place

The extreme sea levels 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 extreme sea level.

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

Extreme sea level 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 extreme sea level 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.

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[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 4: How to obtain the data

The data produced by this project can be obtained under Open Government License from www.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 UK National Tide Gauge Network (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.

– 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 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).

Ordnance Datum Newlyn 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, Ordnance Datum Newlyn). Heights measured using a GPS can be converted to Ordnance Datum Newlyn via the spatial surface of the transformation model OSGM15, or previously OSGM02.

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

The coastal flood boundary (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.

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 shapefile of 2km return levels available on data.gov.uk 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.

4. Update of extreme sea levels

The best practice guidance provided in this user guide updates and replaces that provided previously by Environment Agency (2011). This project was set up to develop and apply better methods to update CFB datasets, using a longer data record.

4.1. Additional gauge data

A key objective of this 2018 update was to extend the gauge data records used in the extreme sea level analysis with new data. Since the original study was commissioned in 2008, nearly 10 years of additional observational data have been recorded at UK NTGN sites and were available for use in this re-analysis. The project also used supplementary data available at NTGN sites. Overall, these additional data have resulted in relatively significant increases in the data record length at many NTGN sites.

4.2. Methodology improvements

New sea level science was also available for this 2018 update. As in the original study (Environment Agency 2011), the extreme sea level analysis was conducted using the skew surge joint probability method. Skew surge is the difference between an observed high tide and the nearest predicted high tide, regardless of timing. This approach provides separate analyses for the distribution of the deterministic tide and the stochastic weather-driven storm surge components of sea level. The improvements can be summarised as follows:

- **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 consistency of levels at each tide gauge
- **Improved statistical fitting** – improvements to the statistical method to avoid bespoke changes and ensure a consistent approach that can be applied in the future
- **Improved confidence intervals** – more complete determination of uncertainty in the statistical method

4.3. Addition of estuary levels

Another significant update in 2018 is the addition of extreme sea levels along priority tidal rivers and estuaries. These data are often needed in fluvial studies that require an understanding of extreme sea level conditions at the downstream boundary. Estuary locations have seen significant flooding recent years, such as the Humber Estuary in 2013, and so there is a strong need to understand risk due to extreme sea levels in these locations.

4.4. Changes in levels

For most gauge sites, the extreme sea levels in the 2018 update have not changed significantly since those published in Environment Agency (2011). Differences of less than 0.1m are not considered significant as these are within the accuracy of extreme sea level estimation. Only 2 gauge sites – 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. For the 200-year return period water levels, locations with changes larger than a magnitude of 0.1m are shown in Table 4.1.

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 return period (m)
Mumbles (Wales)	0.17
Newport	0.10
Cromer (England)	-0.19
Barmouth (Wales)	0.14
Felixstowe (England)	-0.18

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 the 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 and inclusion of large recent event such as the December 2013 event along the East Coast. Most of the larger changes to the 200-year return period are observed in the south-east England tidal gauges.

The confidence levels have also changed slightly for this 2018 update. 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 the 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.

Some differences in the 2km spaced return levels between this update and Environment Agency (2011) are larger than those observed in the gauges. This is primarily due to differences in interpolation methods using a tide-surge model and improved validation using additional data. These larger differences are observed particularly where return levels change quickly across short distances around the coastline. Areas of change include:

- Severn Estuary
- Pentland Firth
- Mersey Estuary
- Solway
- Llŷn Peninsula Chesil Beach
- John o' Groats

5. Description of GIS shapefiles

5.1. Introduction

The results are supplied in GIS format for use by practitioners with standard software. This section describes the content of the shapefiles, which are available on https://environment.data.gov.uk/. Details of the shapefiles are given in Table 5.1.

Table 5.1: Shapefile descriptions

Shapefile name	Description
CFB_Estuary_Boundaries_2018.shp	Inland estuarine boundaries and limits of the extreme sea levels
CFB_Extreme_Sea_Levels_2018.shp	Extreme sea levels and confidence levels[1] for a range of return periods
CFB_Extreme_Sea_Levels_Estuary_2018.shp	Extreme sea levels and confidence levels for a range of return periods within estuary, tidal river, loch, lough and harbour locations
CFB_Surge_Shapes_2018.shp	Reference to surge shape appropriate for each UK NTGN gauge site and where to apply it
CFB_Gauge_Data_2018.shp	Locations of gauges used in extreme sea level analysis

Notes: [1] Confidence levels provide allowances for uncertainty.

5.2. Extreme sea levels

Each point is referenced to both its locality (that is, island, river, lough or loch location) and chainage position in kilometres.

The chainage forms a line around the coast of the UK. Along open coastal areas of the UK mainland and islands, levels are provided at 2km locations. The zero chainage point for the UK mainland is at Newlyn. Where provided previously for Environment Agency (2011), the locations and chainage references remain the same. Within estuaries, harbours, loughs, lochs and tidal rivers, each point is referenced to both a unique ID along the river and the open coastal chainage on which the levels are based; for example, '_270_4' where 270 is the open coast chainage point and 4 is the unique ID.

Extreme sea levels (relative to Ordnance Datum or local datum OD) and confidence levels of AEP ranging from 100% to 0.01% (average return period 1, 5, 10, 20, 25, 50, 75, 100, 150, 200, 250, 300, 500, 1,000, and 10,000 years) are provided for all points.

Confidence levels provide allowances for uncertainty. The 2.5% and 97.5% confidence levels associated with an extreme sea level estimate are the values such that, in the interval between these values, there is a 95% probability of observing the true extreme sea level. This interval is often referred to as the 95% confidence interval and is commonly used to quantify the uncertainty associated with parameter estimates of a statistical model. The 2.5% and 97.5% confidence levels are provided and referred to as 'C1_' and 'C2_' respectively.

The GIS shapefile (CFB_Estuary_Boundaries_2018.shp) contains metadata and extreme sea level values for all output points (Table 5.2).

Table 5.2: Extreme sea level shapefile description

Metadata attribute	Description
Location	Reference to location on the particular chainage
Chainage	This links the point to a chainage
Base year	The year for which the extreme sea levels are valid
HAT	Highest astronomical tide level
MHWS	Mean high water spring tide level
Return periods	Return period (1 to 10,000 years) extreme sea level value
Confidence levels	Confidence level (1 to 10,000 year) 2.5% (C1) and 97.5% (C2) extreme sea level value

5.3. Predicted tide levels

The 2018 update provides predicted HAT and MHWS levels at locations where information is available. These levels are given in shapefiles CFB_Extreme_Sea_Levels_2018.shp (or CFB_Extreme_Sea_Levels_Estuary_2018.shp in estuaries) available on data.gov.uk. Where the predicted tide levels are not available, a default value of 9,999 is given.

The HAT and MHWS levels are based on interpolated levels at locations between NTGN gauge sites and should be used for flood risk management purposes only. If tide levels are required for navigation, please use Admiralty Tide Tables.

5.4. Surge shapes

The surge shape affects the length of time total sea level is elevated by surge above a particular sea level. A wider surge shape results in prolonged high sea levels therefore it is important to apply a representative surge shape in deriving a total storm tide curve. Guidance is given below on the standard surge shapes to use. Two examples of provided surge shapes are shown in Figure 5.1.

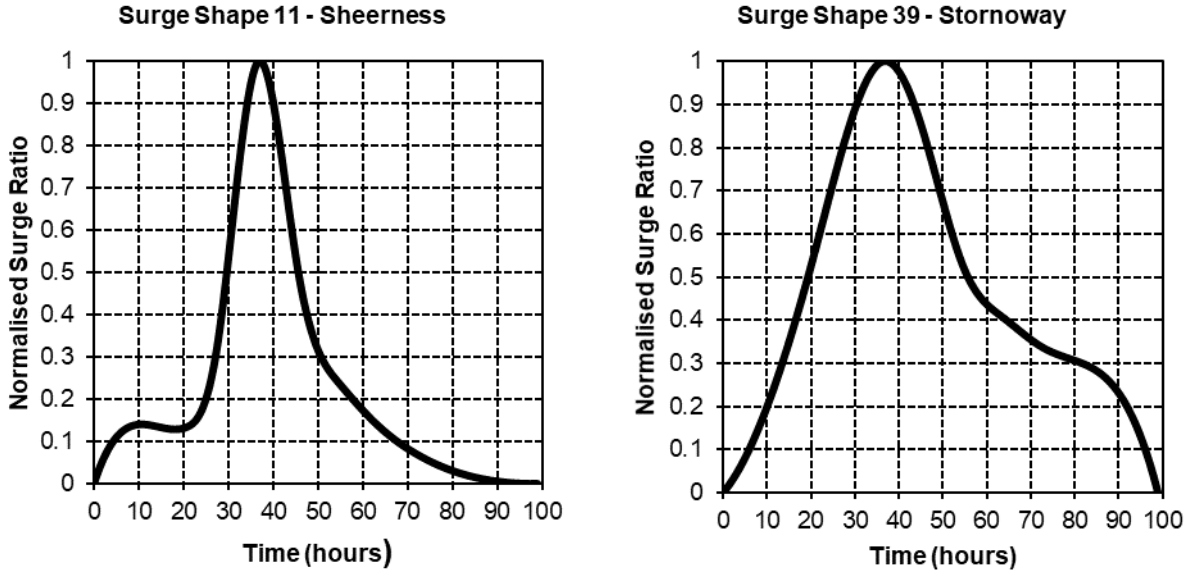


Figure 5.1: Example surge shapes: Sheerness and Stornoway

The GIS shapefile (CFB_Surge_Shapes_2018.shp) contains metadata for each surge shape (Table 5.3). The surge shapes provided are based on analysis of data from 43 tide gauge sites (Table 5.4). Included in the shapefile is a reference to the respective section of coastline where each surge tide shape can be applied. Each shape is given as a time series of values representing the growth and decline of an extreme storm surge typical to the respective location.

The Microsoft® Excel spreadsheet (Design Surge Shapes.xls) accompanying the surge shape shapefile contains the following information.

- Tab 1 (Locations) contains a table referencing the surge shape assigned for each tide gauge site (Table 5.4). The 'Surge Profile' refers to the surge shape values, which can be found in Tab 2 ('Donor Surge Shapes'). The 'Donor Site' is the tide gauge site where the surge shape analysis was performed. The table also gives advice on where each donor surge shape can be applied. The named sites reference geographical bounds moving clockwise around the coast of the UK.
- Tab 2 (Donor Surge Shapes) gives values of the surge shapes for a duration of 99 hours at 15-minute intervals for each of the surge donor sites.

The remaining worksheets present figures showing the 43 surge shapes.

Table 5.3: Surge shape shapefile description

Metadata attribute	Description
Profile	Reference to the Surge Shape number in the accompanying spreadsheet
Donor site	Tide gauge where analysis to produce the surge shape was made
Location	Geographical bounds where surge shape applies

Table 5.4: Surge shapes for Class A sites and the geographical frontages to apply these profiles

Surge shape	Donor site	Apply from (clockwise around UK):
1	Wick	John o’ Groats to Brora
2	Moray Firth	Brora to Lossiemouth (Moray Firth)
3	Aberdeen	Lossiemouth to Arbroath
4	Leith	Arbroath to North Berwick (including 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 (incl. Thames Estuary)
12	Dover	Margate to Selsey

Surge shape	Donor site	Apply from (clockwise around UK):
13	Portsmouth	Selsey to Milford-on-Sea (including 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 (Cei Newydd)
26	Barmouth	New Quay (Cei Newydd) to Aberaeron Bay
27	Holyhead	Aberaeron Bay to Amlwch
28	Llandudno	Amlwch to Point of Ayr
29	Liverpool	Point of Ayr to Fleetwood
30	Heysham	Fleetwood to Haverigg Point (including Morecambe Bay, Duddon Estuary)
31	Workington	Haverigg Point to Isle of Withorn (including Solway Firth, Wigtown Bay)
32	Port Erin	Isle of Man, Ballyhalbert to Warrenpoint
33	Portpatrick	Isle of Withorn to Girvan
34	Millport	Girvan to Mull of Kintyre (including 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

6. Using the results

6.1. Introduction

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 extreme sea levels for various purposes, including:

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

6.2. Choosing an extreme sea level

This project has produced extreme sea levels around the coast of the UK. This section describes how to select an extreme sea level for a site.

1. Ensure site is within boundaries of this project

The update has provided extreme sea levels for all open coast points and some locations in estuaries, loughs, lochs, tidal rivers and harbours. For those estuarine locations not included in the update, please refer to the estuary 'cut-off' lines as indicated by the shapefile CFB_Estuary_Boundaries_2018.shp. If the site is upstream of the estuary boundary, the extreme sea level cannot be obtained directly from the results of project.

In some cases for modelling studies, it may be appropriate to take open coast rather than estuarine levels and extend the model domain accordingly. This will depend on the individual application and details of the estuarine model used. Further information on the individual estuarine models can be obtained from the relevant national agency.

2. Find site

The coastal chainage is presented in the shapefile CFB_Extreme_Sea_Level_2018.shp (or CFB_Extreme_Sea_Level_Estuary_2018.shp in estuaries). The chainage is provided slightly offshore for ease of viewing in mapping software.

The chainage points are perpendicular to the site which they represent. Given the complex alignment of the coastline, this coastal chainage is not precise. Practitioners are recommended to pick the closest chainage point to the site of interest in a perpendicular direction from the coast. This should be simply done 'by eye' as the accuracy of the sea level values does not warrant a more rigorous selection process.

3. Choose return period sea level

Linked to each chainage point are 16 peak sea levels, that is, the levels having an AEP ranging from 100% to 0.01% (1 to 10,000 year return periods). Although levels are given to 2 decimal places, practitioners should treat them as only accurate to 1 decimal place.

The levels are only quoted to 2 decimal places as an aid to assess the variation between locations when selecting an appropriate chainage point.

4. Confidence levels

This update provides estimates of sea level ranging from AEPs from 100% to 0.01% (1 to 10,000 year return periods). The length of data record used for the estimation is limited, in most cases, to less than 100 years and hence there is a degree of uncertainty associated with the values. Confidence levels are provided in the same shapefile as above (CFB_Extreme Sea_Levels_2018.shp or CFB_Extreme Sea_Levels_2018_Estuary.shp in estuaries). It is important to consider these confidence levels when conducting sensitivity testing in a study or design.

In some cases, there may be additional uncertainty in the levels associated with models used to interpolate levels between gauges or within estuaries. Further information on the approach used can be found in the technical report.

As well as considering the CFB confidence levels in sensitivity testing in a study or design, other factors that may have an impact on extreme sea levels should also be taken into account. Examples of such factors are uncertainty in sea level rise projections and missing local processes such as wave set-up (see Note 2 at the end of Section 6.3.2).

5. Climate change allowances

As mean sea levels increase due to climate change, extreme sea levels will also increase. The extreme sea levels provided are to a base year of 2017. For future extreme sea levels, an appropriate allowance should be added for sea level rise.

6.3. Generating design tide curves

Four components are required to generate a design tide curve for any given site:

- Extreme sea level (see Section 6.3.1)
- Base astronomical tide curve (see Section 6.3.2)
- Surge component (see Section 6.3.3)
- Corrections for sea level rise (see Section 6.3.4)

6.3.1.Extreme sea level

Select an extreme sea level for a site as described in Section 6.2.

6.3.2.Base astronomical tide curve

– Step 1: Identify Standard Port

This method of generating a base tide curve involves using Admiralty Tide Tables. First select the Standard Port for your site from Part II of the Admiralty Tide Tables.

– Step 2: Choose a predicted high tide level between HAT and MHWS

The base astronomical tide should be high enough to represent a larger than 'normal' event but also to reach an appropriate level which reflects an event that occurs every year. It is common practice to base a design tidal graph on a spring tide. However, spring tides vary substantially over time due to the influence of the lunar cycle. Using a level between HAT and MHWS is therefore recommended. The tide chosen must be lower than the chosen extreme sea level. This should be checked as the HAT level is larger than the 1 in 1-year extreme sea level at some UK locations.

Select a level between HAT and MHWS for the Standard Port. Table V in the Admiralty Tide Tables contains HAT values for Standard and Secondary Ports. Values of MHWS can be derived from Part II of the Admiralty Tide Tables. If this information is not available, HAT and MHWS levels are provided for some sites in the shapefile CFB_Extreme_Sea_Levels.shp (or CFB_Extreme Sea_Levels_Estuary_2018.shp in estuaries).

– Step 3: Identify date and time for selected level between HAT and MHWS

Part I of the Admiralty Tide Tables contains predicted times and levels for high and low tides for a one-year duration. In the tables, find the level between HAT and MHWS for the Standard Port and its respective date and time. If this level is not contained in the predictions, simply select a lower level ensuring it is higher than MHWS.

– Step 4: Choose a base astronomical tidal cycle duration

Choose a duration for the base astronomical tidal cycle depending on your requirements. The date and time of your selected high tide (between HAT and MHWS) should be the centre of the base astronomical tide. Extending the tide curve to 2 days before the peak and 2 days after is recommended, giving a total duration of approximately 100 hours. This will ensure an adequate number of high tides is included.

– Step 5: Identify harmonic constraints

The preceding steps have identified a base tide event in terms of date, time and peak level. In order to produce the base astronomical tide curve, it is necessary to identify harmonic constants. The harmonic constants represent the multiple influences which contribute to an astronomical tide including:

- the rotation of the Earth
- the positions of the Moon and the Sun relative to Earth
- the Moon's altitude above the Earth
- bathymetry

Part III of the Admiralty Tide Tables contains the 6 largest harmonic constants for Primary and Secondary Ports required to generate a base astronomical tide curve. Select the harmonic constants for your site including any seasonal corrections applicable to the dates of the identified base tide event. Use the closest port in the Admiralty Tide Tables if your site is not referenced.

– Step 6: Generate base astronomical tide curve using standard software

Software to generate tide curves is readily available. If the time of the chosen peak tide is known, input the start date and time, the end date and time, and the harmonic constants to produce the base tide curve. Otherwise, generate a tide curve for a year and look for a suitable tide within the period.

Some tide curve generation software has the harmonic constants inbuilt, in which case Step 5 is not necessary.

– Step 7: Convert datum from Chart to Ordnance Datum

The astronomical tide levels need to be expressed relative to Ordnance Datum, not Chart Datum. Chart Datum refers to the local datum of a site. The extreme sea levels provided for the 2018 update are referenced to either Ordnance Datum Newlyn (England, Wales, Scotland) or Ordnance Datum Belfast (Northern Ireland). Levels at Stornoway, St Mary's, Lerwick and Isle of Man (Port Erin) are given to local datums.

It is important that the base astronomical tide curves and extreme sea levels are referenced to a consistent datum in the total storm tide curve generation. A correction factor at each port site is available from the Admiralty or the UK Hydrographic Office; otherwise contact the national governing body for this information. The correction factor is added to each level in the time series to convert the series to Ordnance Datum.

Notes

1. Astronomical base tide curves for Environment Agency projects

For Environment Agency projects, flood forecasting teams are able to provide astronomical base tide curves. The site location and dates of the desired astronomical tide curve prediction will be required when submitting this request. This information is found by the end of Step 4 above.

2. Modelling of MHWS or HAT only events

Where port information (Standard or Secondary) is available at the site of interest, the astronomical tide should be based on the port information by preference.

Where Standard Port information is not available, the astronomical tide series may be derived from the site MHWS or HAT level provided in the shapefile CFB_Extreme_Sea_Level_2018.shp (or CFB_Extreme Sea_Levels_Estuary_2018.shp in estuaries) and time series information from the nearest port site.

Either a port time series corresponding to the CFB MHWS or HAT peak level can be obtained or a time series with a peak similar to the MHWS or HAT level can be scaled to match the CFB MHWS or HAT level peak.

6.3.3.Surge component

Skew surge is the difference between an observed high tide and the nearest predicted high tide, regardless of timing. The surge itself will include the rise in sea level caused by the pertaining low pressure weather system and its associated storm winds. It does not include for local wave set-up, which can arise near the coastline. Practitioners will need to allow for this effect separately.

In reality, the surge shapes are highly variable between different extreme events. For practical purposes, however, it is convenient to have a standard surge shape that can be applied and used to generate total design event tide curves in a consistent manner for a particular length of the coast. The surge shape will vary between different sections of the coast.

Select the appropriate surge shape for your site using the GIS shapefile CFB_Surge_Shape_2018.shp. A summary of the surge shapes and their suggested zone of application is given in Table 5.4. In some cases, the site may be at the boundary between 2 surge shapes (for example, at Minehead). In this instance, carrying out a sensitivity test using both shapes is recommended.

6.3.4.Resultant curve

Use a spreadsheet to combine the 3 components (target peak sea level, base astronomical tide and surge shape) to produce the resultant tide curve. The time resolution of the tide and surge data in the spreadsheet needs to be the same.

For practical purposes, it is recommended that the extreme sea level, peak astronomical tide level and peak surge height should occur coincidentally. Therefore, position the surge shape so that its peak height is coincident in time with the peak level in the base tide sequence. Scale the surge shape from its unit height of 1 such that the surge height added to the peak of the base tide equals the target peak sea level desired. Adding the scaled surge heights to the base tide levels gives the net design event tide curve. An example is shown in Section 7.

Sensitivity tests for the peak surge occurring before or after the base of the peak astronomical tide may be appropriate depending on the purpose of the study or assessment. Ensure the scaling factor is altered to reflect the lower surge shape value now coincident with the peak of the base astronomical tide curve. Be careful that this scaling factor still achieves the desired peak sea level. If this does not occur, adjust the scaling factor by trial and error until the required result is obtained.

6.3.5.Sea level rise allowances

The extreme sea levels provided are to base year 2017. For future extreme sea levels, it is important to consider allowances for increases due to sea level rise. Contacting your national governing body for the appropriate guidance is recommended. The rise in level for future scenarios applies to all levels in the resultant tide curve, not just the peak levels.

7. Worked example

The worked example demonstrates how a practitioner can use the data to select relevant sea level information for a coastal site. An example at Clovelly in north Devon is used for illustrative purposes. The following steps should be carried out when determining a design tide curve:

1. Check study location is within the boundaries for this project
2. Select an appropriate chainage point for extreme sea levels
3. Select an AEP peak sea level
4. Consider allowance for uncertainty
5. Identify base astronomical tide
6. Convert levels to Ordnance Datum
7. Scale the base astronomical tide curve to a level between the CFB HAT or MHWS levels (
8. Identify surge shape to apply
9. Produce the resultant design tide curve
10. Apply allowance for climate change
11. Perform a sensitivity test.

– Step 1: Check study location is within the boundaries for this project

Open the CFB_Estuary_Boundaries_2018.shp shapefile to show the estuary boundaries. If the site is upstream of the estuary boundary, the extreme sea level cannot be obtained directly from the results of the 2018 update.

A location plan for Clovelly is presented in Figure 7.1. Clovelly is found on the open coast and so is within the coverage of this project. Some levels are provided for estuary locations but not all, and levels should not be applied beyond the estuary boundary limits given in the shapefile.

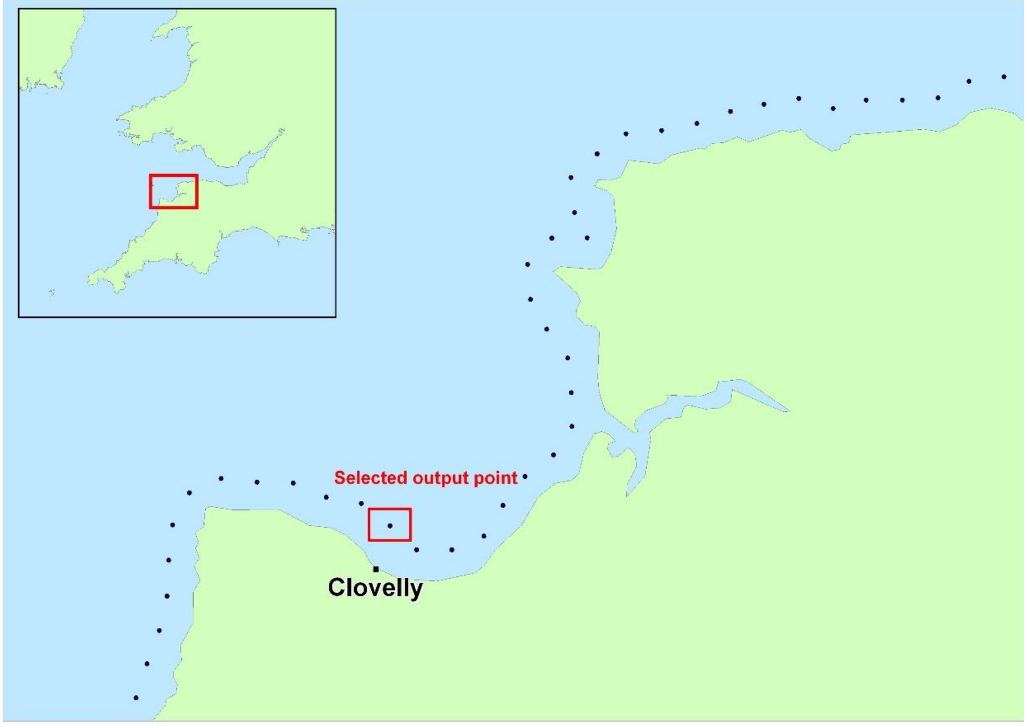


Figure 7.1: Location Plan for Clovelly

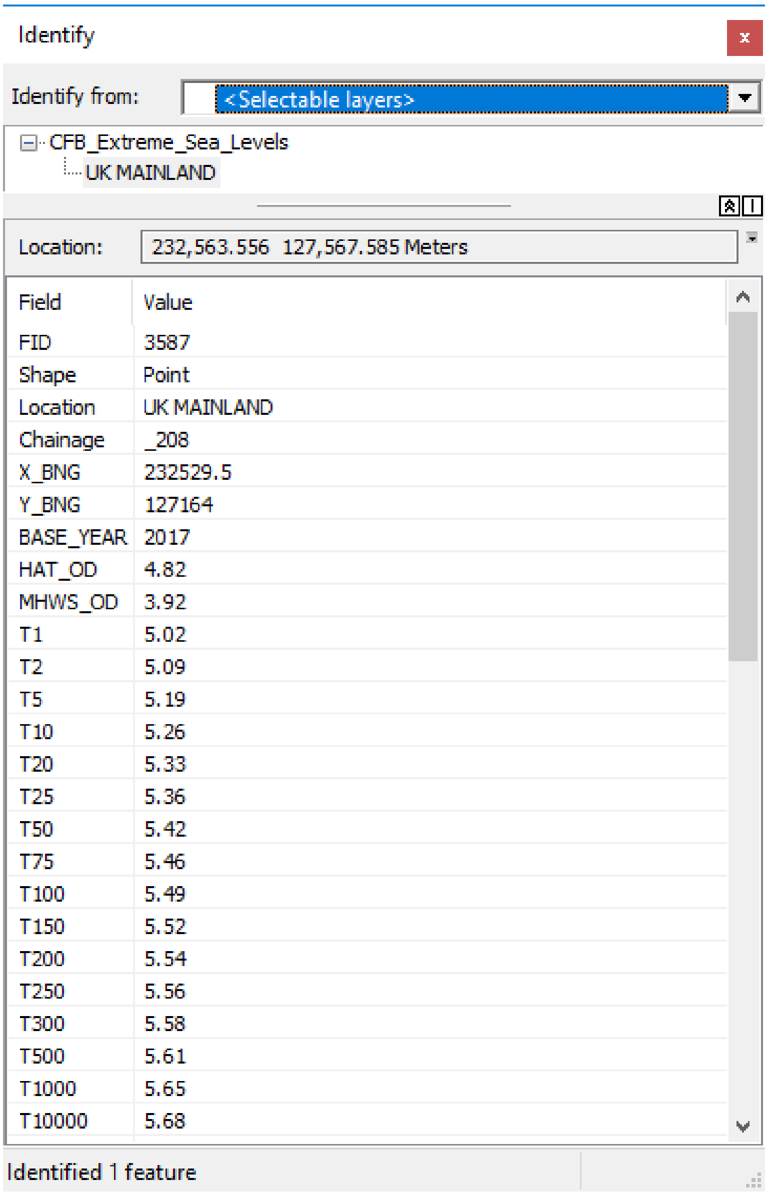
– Step 2: Select an appropriate chainage point for extreme sea levels

Open the shapefiles CFB_Extreme_Sea_Levels_2018.shp (or CFB_Extreme_Sea_Levels_Estuary_2018.shp in estuaries) in a standard GIS program.

Using the location of your site as a guide, simply draw a line perpendicular from the coastline to nearest chainage point. The accuracy of the sea level values does not warrant any more rigorous selection process. The coastal chainage point for this worked example is 208km (see Figure 7.1).

– Step 3: Select an AEP peak sea level

In the GIS program, click on the selected chainage point using the identification tool or open up the attribute data table to access the point metadata. This will open a table. The fields with the prefix 'T' are the return periods from 1 to 10,000 years and the corresponding sea level values are given in metres relative to Ordnance Datum.[2] The location and chainage are also given. Figure 7.2 shows how this will appear using the identification tool.



Field	Value
FID	3587
Shape	Point
Location	UK MAINLAND
Chainage	_208
X_BNG	232529.5
Y_BNG	127164
BASE_YEAR	2017
HAT_OD	4.82
MHWS_OD	3.92
T1	5.02
T2	5.09
T5	5.19
T10	5.26
T20	5.33
T25	5.36
T50	5.42
T75	5.46
T100	5.49
T150	5.52
T200	5.54
T250	5.56
T300	5.58
T500	5.61
T1000	5.65
T10000	5.68

Figure 7.2: Metadata for Clovelly from CFB_Extreme_Sea_Levels_2018.shp

[2] Ordnance Datum Belfast in Northern Ireland, Ordnance Datum Newlyn elsewhere in the UK, except at Stornoway, Lerwick and St. Mary's which have local datums.

For this example, it is assumed that the 1 in 200 year (0.5% AEP) level is the target peak for the intended analysis. This level is 5.54mOD (Table 7.1).

Table 7.1: Extreme sea levels for Clovelly

Return period (years)	Chainage 200km extreme sea levels (m Ordnance Datum)
1	5.02
2	5.09
5	5.19
10	5.26
20	5.33
25	5.36
50	5.42
75	5.46
100	5.49
150	5.52
200	5.54
250	5.56
300	5.58
500	5.61
1,000	5.65
10,000	5.68

– Step 4: Consider allowance for uncertainty

At this point, decide whether the study requires a consideration of uncertainty. The confidence levels contained within the shapefile'CFB_Extreme_Sea_Levels_2018.shp for each return period for each point have the prefix 'C1' (2.5% confidence level) and 'C2' (97.5% confidence level). Depending on the study's requirements, the 2.5% confidence level may be considered a reasonably likely lower sea level for the given return period, while the 97.5% level may be considered a reasonable upper limit of the likely sea level for the given return period. Uncertainty information for Clovelly is shown in Table 7.2.

As per Note 9 in Section 3.1, these confidence levels take account of the uncertainty associated with the statistics only. Additional uncertainties may include those associated with sea level rise due to climate change and model uncertainty (if using an estuary chainage point). These should also be considered.

Table 7.2: Confidence intervals for Clovelly

Return period (years)	Chainage 208km 2.5% confidence levels (m)	Chainage 208km 97.5% confidence levels (m)
1	5.01	5.03
2	5.08	5.11
5	5.17	5.21
10	5.24	5.29
20	5.3	5.36
25	5.32	5.39
50	5.39	5.47
75	5.43	5.52
100	5.45	5.55
150	5.48	5.61
200	5.49	5.64
250	5.5	5.67
300	5.51	5.7
500	5.53	5.77
1,000	5.55	5.86
10,000	5.48	6.14

– Step 5: Identify base astronomical tide

Select a level between the HAT and MHWS levels from the closest available port and identify an astronomical tide that corresponds to this level. Table 7.3 presents HAT and MHWS levels for Clovelly and Milford Haven (the Standard Port used for Clovelly). The mid-point level has been selected. The tidal predictions are taken from the 2010 Admiralty Tide Tables Volume 1 (United Kingdom and Ireland) (UKHO 2010).

Table 7.3: MHWS, HAT and nominated peak base tide level (m Chart Datum)

Site name	MHWS	HAT	Base tide curve level
Clovelly	8.3	9.2	8.75
Milford Haven	7.0	7.9	7.45

The next step requires the user to find a similar level in the Admiralty Tide Tables. Clovelly is not a Standard Port and so predicted tides are not provided in the Admiralty Tide Tables (though they may be available in other publications). Therefore, tide prediction tables for the appropriate Standard Port (Milford Haven in this example) should be used to identify the dates of an appropriate tide event. The tables are in Part I of the Admiralty Tide Tables.

The target high tide level for the astronomical tide should be the level between HAT and MHWS, selected above. Sufficient event duration is 2 days before and after the peak tide level. An example tide event to use is shown in Table 7.4.

In practice it is perfectly adequate for the calculated peak base tide level to be near to the target peak; an exact match is not necessary.

Table 7.4: Tide curve durations

Site name	Peak level (m Chart Datum)	Date and time of peak	Design tide curve dates
Milford Haven	7.5	30 March 2010, 06:08	28 March 2010 to 1 April 2010

Select harmonic constants for your site from Part III of the Admiralty Tide Tables. The harmonic constants are required to generate the base astronomical tide curve. In this instance, there are no harmonic constants for Clovelly. Use of the nearest suitable Standard/Secondary Port is therefore recommended – in this case, Lundy. Use software to generate the base tide curve for the dates selected.

– Step 6: Convert levels to Ordnance Datum

The levels in Admiralty Tide Tables are quoted to Chart Datum but the extreme sea level estimates are quoted to Ordnance Datum. The conversion between Chart Datum and Ordnance Datum in the UK can be found in Table III of the Admiralty Tide Tables, Admiralty Charts or obtained from the UK Hydrographic Office.

The Chart Datum to Ordnance Datum conversion for Clovelly is shown in Table 7.5.

Table 7.5: Chart Datum to Ordnance Datum conversion for Clovelly

Site name	Chart Datum to Ordnance Datum conversion
Clovelly	-4.40

Use this value to convert the levels of the base astronomical tide so they relate to Ordnance Datum. The peak base tide level becomes 4.35m Ordnance Datum (that is, 8.75m Chart Datum – 4.40m).

Paste the values (time and level) of the base tide into a site-specific spreadsheet. To match the surge shape data provided, values are needed for every 15 minutes.

– Step 7: Scale the base astronomical tide curve to the HAT or MHWS level given in CFB_Extreme_Sea_Levels_2018.shp (or CFB_Extreme_Sea_Levels_Estuary_2018.shp in estuaries)

HAT and MHWS levels are provided at many sites for this 2018 update on coastal flood boundaries.

If the nearest port to the site is not very close, then it may be necessary to scale the base astronomical tide curve to the HAT or MHWS levels provided by the update. This is achieved by dividing each level in the time series by the peak value and multiplying by the CFB HAT or MHWS level.

If the peak astronomical tide level already falls between the provided HAT and MHWS levels, then this step is not required. As Clovelly has a nearby port, this step is therefore not required in this example.

– Step 8: Identify surge shape to apply

The steps so far have led to selection of an extreme sea level and a base astronomical tide curve that reaches a peak between HAT and MHWS. It is now necessary to apply a surge shape to the base tide.

The surge shape shapefile shows that the surge shape to use for Clovelly is the one from Ilfracombe (Figure 7.3). In the Design Surge Shapes spreadsheet, open the worksheet called Donor Surge Shapes. Copy the time in hours (first column) and the surge values for shape 19 (Ilfracombe) and paste these into the site-specific spreadsheet.

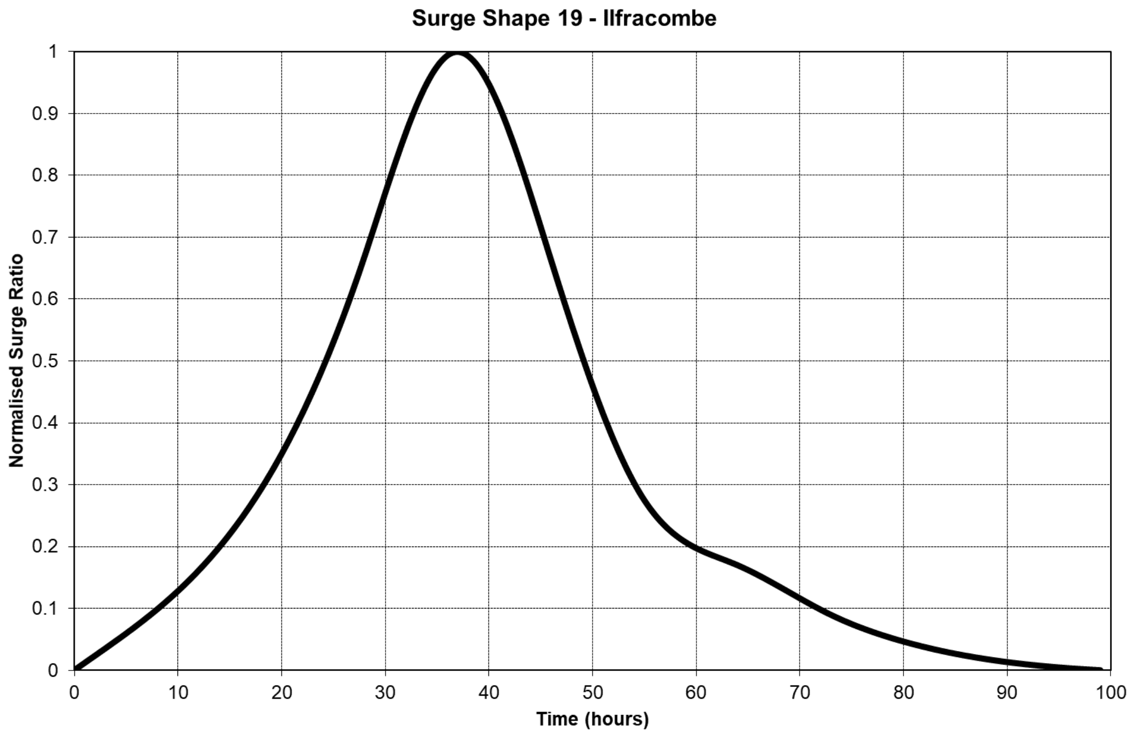


Figure 7.3: Surge shape for Ilfracombe

– Step 9: Produce the resultant design tide curve

Using the site-specific spreadsheet, the 3 components of the design tide curve (extreme sea level, base astronomical tide curve and surge shape) can be combined to produce the resultant design tide curve. In this example, the peaks of the astronomical tide and the surge shape are set to coincide at the same time.

The peak of the base tide curve is 4.35m Ordnance Datum (see Step 6). The target level as identified in Step 2 is 5.54m Ordnance Datum. It is therefore necessary to scale the surge shape according to the difference between the target level and the peak of the astronomical tide curve; here this is 1.19m.

The peak of the surge shape and of the base astronomical tide curve are aligned at the same time and so the peak surge shape ordinate at this point is 1.0. Therefore, the scaling factor to apply to all surge shape values is 1.19/1.0 = 1.19.

Adding the scaled-up surge shape values to the astronomical tide levels creates the net design tide curve. Figure 7.4 shows the base astronomical tide curve, scaled-up surge shape and resultant design tidal graph for Clovelly. This is the recommended tide curve to use with the 0.5% AEP (200-year return period) event at Clovelly.

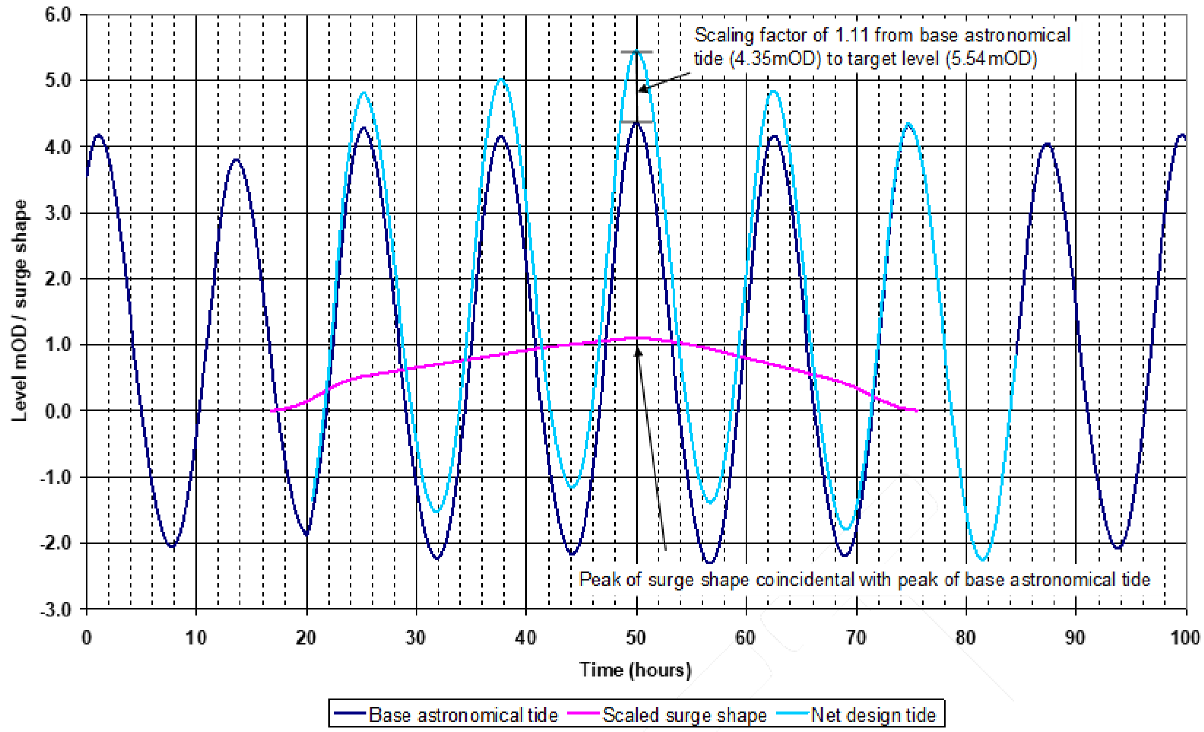


Figure 7.4: Resultant design tide curve for Clovelly

– Step 10: Apply allowance for climate change

The 2018 update has not provided predictions of future sea level rise due to the influence of climate change. It is recommended that national guidance be consulted to derive allowances for climate change. The relevant national environment agency can be contacted to clarify which guidance may be applied. This allowance for sea level rise should be added to each level in the entire design tide curve.

– Step 11: Perform a sensitivity test

As a sensitivity test, one can consider a case where the peak of the surge component is offset from the peak of the base astronomical tide. The example shown here considers moving the peak of the surge shape to 2 hours before the peak of the astronomical tide curve.

The surge shape ordinate now coincident with the peak of the astronomical tide is the value at 2 hours after the surge peak. In this instance the value becomes 0.97 instead of 1.0. Our target level (5.54m Ordnance Datum) and the base astronomical tide curve peak (4.35m Ordnance Datum) remain the same. The scaling factor thus becomes 1.23 (1.19 divided by 0.97). This is applied to all the surge shape values.

The net tide curve with the peak of the surge applied 2 hours before the peak of the astronomical tide curve is shown in Figure 7.5.

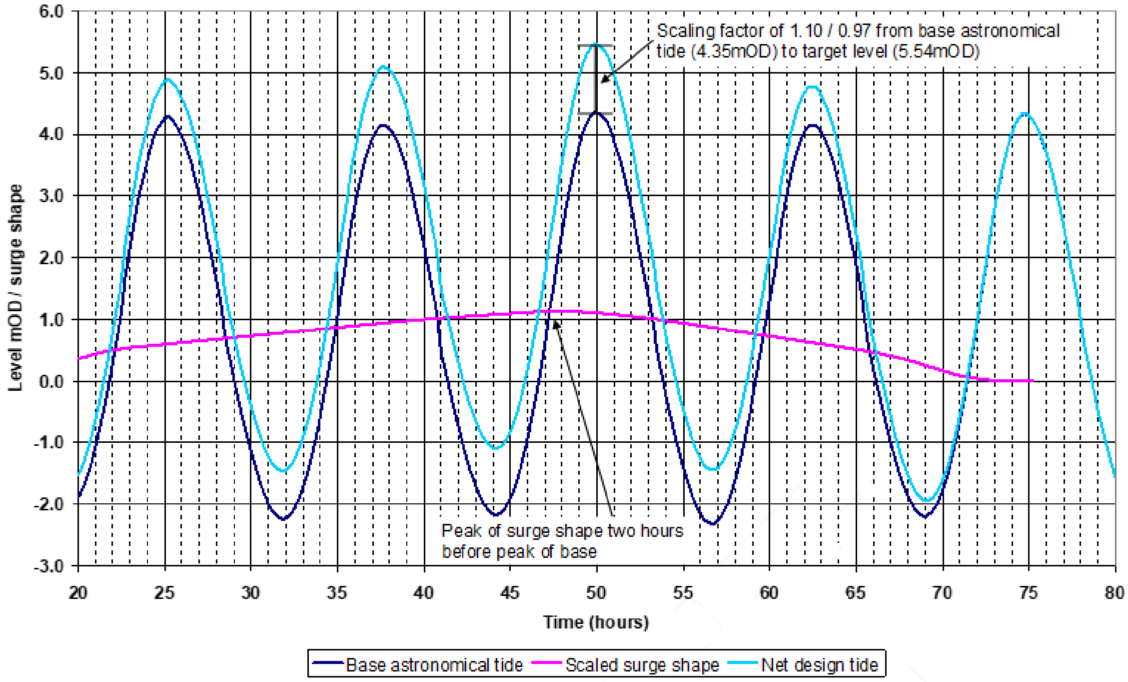


Figure 7.5: Peak surge occurring 2 hours before peak base tide

8. References

ENVIRONMENT AGENCY, 2011. Coastal Flood Boundary Conditions for UK Mainland and Islands. Design Sea Levels. Report SC060064/TR2. Bristol: Environment Agency.

UKHO, 2009. Admiralty Tide Tables. Volume 1, 2010: United Kingdom and Ireland including European Channel ports. Taunton: United Kingdom Hydrographic Office.

9. Acknowledgements

The work described in this report is based on activities by the project team for the UK Coastal Flood Forecasting partnership on behalf of the Environment Agency, the Scottish Environment Protection Agency, the Department for Infrastructure Northern Ireland and Natural Resources Wales.

The lead consultant for this project was JBA Consulting. The following members of the project team contributed to the work as follows.

- 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

10. List of abbreviations

AEP	annual exceedance probability
CFB	coastal flood boundary
GIS	geographical information system [software]
HAT	highest astronomical tide
MHWS	mean high water spring tide
NTGN	National Tide Gauge Network

Appendix: Study area maps

Figure A.1: Location of CFB update levels, estuary levels and models – south and east England

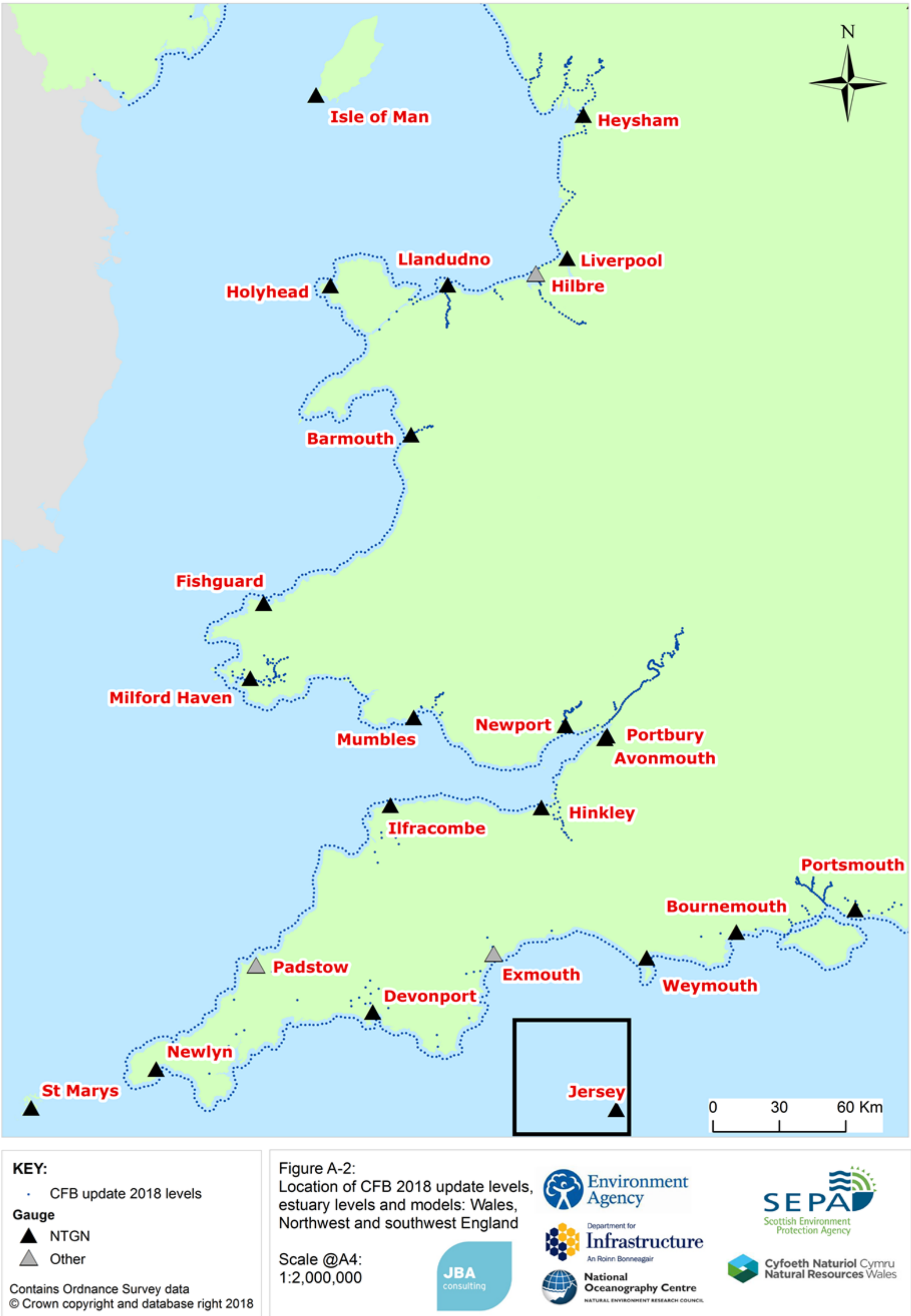


Figure A.2: Location of CFB update levels, estuary levels and models – Wales, north-west and south-west England

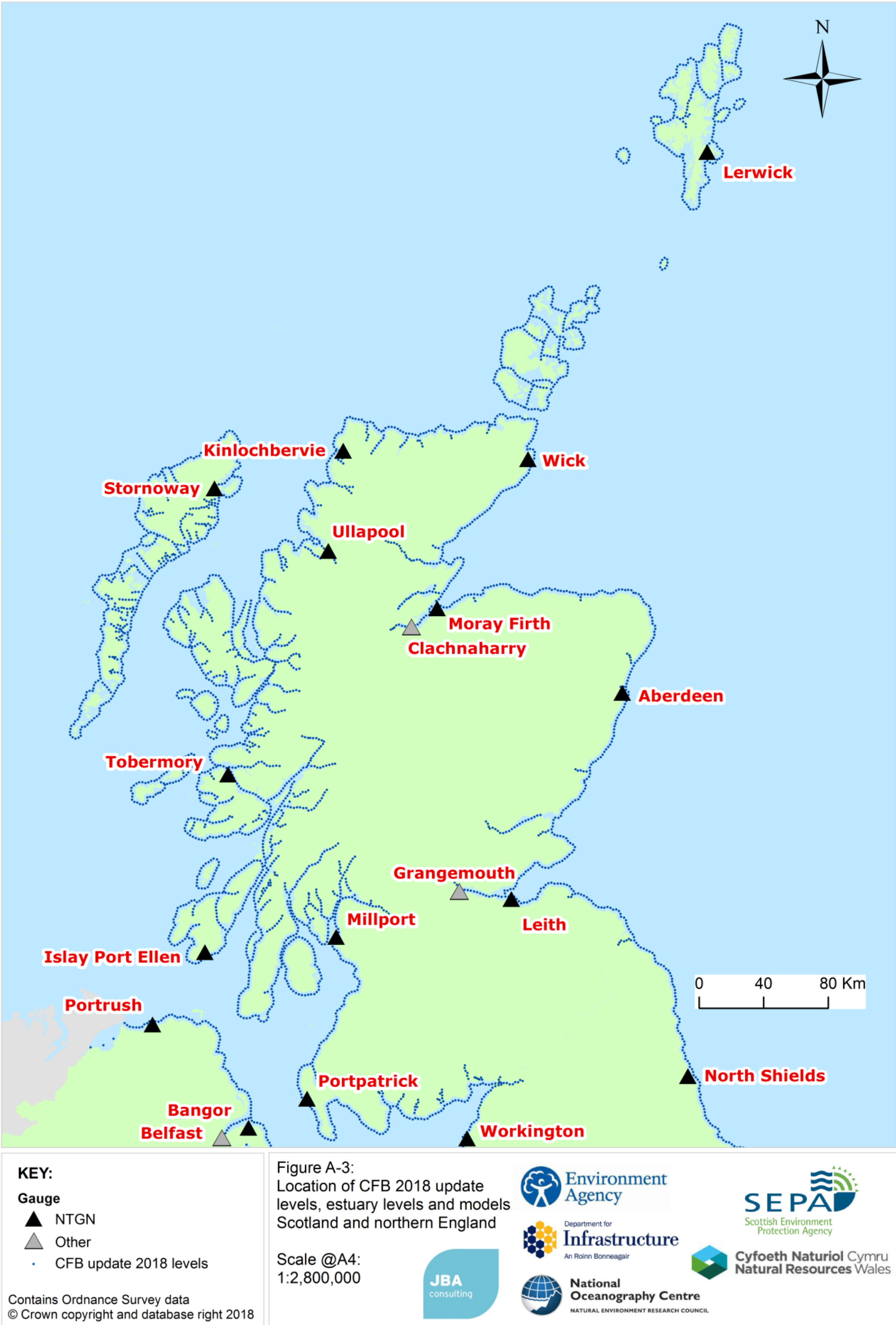


Figure A.3: Location of CFB update levels, estuary levels and models – Scotland and northern England

Figure A.4: Location of CFB update levels, estuary levels and models – Northern Ireland

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