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Coastal flood boundary conditions for UK mainland and islands

Project: SC060064/TR2: Design sea levels

Flood and Coastal Erosion Risk Management Research and Development Programme

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Miranda Kavanagh

Miranda Kavanagh

Director of Evidence

Executive summary

Successful risk-based flood and coastal risk management requires the best available information on coastal flood boundary conditions. Current information on design sea level conditions is not consistent around the country and is becoming out of date.

This project aimed to overcome these shortcomings by using up-to-date tidal records, by applying a consistent method incorporating the best available statistical techniques, and by providing values on design sea levels at a regular close spacing around the coastline. An additional product, not previously available at a national scale, is the means of generating appropriate storm tide curves.

The challenge of this project was to estimate sea levels which might occur for return periods considerably greater than the length of the dataset on which these extremes are based.

The foundation of the analysis was tide-level data as recorded at 40 Class A gauge sites within the study area, together with equivalent data from other sites. Statistical analysis was done for the Class A sites, and for another five sites included as primary sites, to generate probabilities of predicted high tide and of skew surge. Combining these two elements gave the overall design sea level probabilities, expressed here in terms of levels attributed to their respective average return period. This analysis used the skew surge joint probability method (SSJPM).

In order to provide complete coverage of return period sea levels around the coastline, and given that using all tide gauge data around the country would be a lengthy exercise, an interpolation method was used to determine return period sea levels between the primary sites. The process was assisted by the use of results from a continental shelf tide-surge model and a similar, more detailed, model of the North East Irish Sea.

The model results could not be used directly, but required a series of corrections to obtain design sea values. As a first step, the model results for nodes at the primary gauge data sites were corrected to accord with values obtained from statistical analysis of the gauge records. Secondly, model results for intermediate nodes were adjusted in line with the corrections made at primary data sites. Thirdly, linear interpolation between model nodes was used to give return period sea level values at about two-km spacing along a nominal coastal chainage line.

Finally, a further check and adjustment was applied to ensure the return period levels were plausible. This involved comparing design sea levels along the coastal chainage line with the apparent return period of high levels as indicated by the secondary tide gauge data, being all the data other than that used for the primary analysis.

The results from this project are derived from the best available data using the best available techniques. Their derivation involved careful thought, intelligently applied, in conjunction with mathematical analyses. As such, the results should be as sound as is reasonably possible at the present time. However, this does not necessarily mean that the results are wholly accurate and will remain valid for all time.

Acknowledgements

The word described in this report is based on activities by the project team for the Joint Department for Environment, Food and Rural Affairs/Environment Agency R&D project *Coastal flood boundary conditions for UK mainland and islands* (SC060064).

The lead consultant for this project was Royal Haskoning. The following members of the project team contributed to the work as follows:

Royal Haskoning – led by Alastair McMillan and David Worth	-	Conceptual processes; modelling calibration and verification; gauge data analysis and reporting
JBA Consulting – led by Mark Lawless	-	Extreme sea level modelling, analysis of surge curves and reporting
National and Tidal Sea Level Facility (NTSLF) – led by Kevin Horsburgh	-	Extreme sea level modelling and reporting
Professor Jonathan Tawn	-	Advice on extreme sea level statistical analyses
Professor Robert Nicholls, University of Southampton	-	Peer review
Douwe Dilligh, Deltares	-	Peer review

Contents

List of tables and figures

1 Introduction

1.1 Background

Successful risk-based flood and coastal erosion risk management requires the best available information on coastal flood boundary conditions. Current information is not consistent around the country and is becoming out of date.

In April 2008 the Environment Agency took on the strategic overview of coasts in England, giving it an overarching role in the management of the English coastline.

This R&D project (SC060064: *Coastal flood boundary conditions for UK mainland and islands*) was set up to develop and apply better methods to update these datasets, using a longer data record.

The aims of the project were to:

- Provide a consistent set of extreme sea levels around the coasts of England, Wales and Scotland (replacing advice given in the Proudman Oceanographic Laboratory Report 112)[1].
- Provide a means of generating appropriate total storm tide curves for use with the extreme sea levels.
- Offer practice guidance on how to use these new datasets.

This report presents the findings from the extreme sea level and storm tide curve studies, together with a description of the data used and method applied. The detailed results are given in GIS files accompanying the report. The practical guidance can be found in a separate document[2].

This project was carried out as part of the Environment Agency/Department for Environment, Food and Rural Affairs Joint Flood and Coastal Risk Research and Development Programme.

The work was conducted by a project team led by Royal Haskoning, and including JBA Consulting, Professor Jonathan Tawn, and the National Tidal and Sea Level Facility (NTSLF), part of the Proudman Oceanographic Laboratory.

The Environment Agency Project Executive was Angela Scott; the Environment Agency's Business User was Tim Hunt and the Environment Agency Project Manager was Stefan Laeger.

The Project Director for Royal Haskoning was Fola Ogunyoye; their Project Manager was Alastair McMillan.

The project was supported by the Scottish Environment Protection Agency (SEPA) and the Scottish Executive

1.2 Current practices and the need for change

The current method for deriving extreme sea levels around the coastline is the POL Report 112, *Spatial analyses for the UK coast*, published in 1997. In addition, a number of regional and local extreme sea level datasets from analysis of respective tide gauge data have also been derived for the Environment Agency and SEPA.

These reports and datasets offer nationally inconsistent extreme sea level values. Inconsistencies apply both to the method of derivation and to the spatial distribution of values. Additionally, for much of the coastline the information provided is based on a much shorter tide level record than is now available.

Our project aimed to overcome these shortcomings by using up-to-date tidal records, by applying a consistent method incorporating the best available statistical techniques, and by providing values at a regular close spacing around the coastline. An additional product, not previously available at a national scale, is a means to generate appropriate storm tide curves.

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.

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 a number of purposes, including those listed below:

- flood risk mapping
- flood risk assessments
- spatial planning
- coastal design
- flood warning
- port operations.

1.3 Study area

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

- Isles of Scilly
- Anglesey
- Isle of Man
- Scottish Islands of the Hebrides, Orkney and Shetland
- Isle of Wight.

Figure 1.1 to Figure 1.6 shows the study area in each region and the boundaries beyond which extreme sea level estimates have not been provided. The figures can be found at the end of the main report.

1.4 Summary of outputs

Key outputs from the project may be summarised as follows:

- Extreme peak sea levels of annual exceedance probability ranging from 100 to 0.01 per cent (average return period one in one year to one in 10,000 years).
- Peak sea level values are given for the full study area coastline at a spacing of about two km. This enables rapid selection of appropriate levels without any need for further interpolation.
- Advice on generating appropriate total storm tide curve for use with the extreme sea levels. Standard surge shapes are given for each part of the coast.

Coverage of extreme sea levels extends around the open coast, together with some outer parts of estuaries. Estuary values are not otherwise provided, because of the individual nature of tidal hydraulics in each estuary, making study more appropriate at a local rather than national level. **Figures 1.1** to **1.6** provide ‘cut-off’ lines, upstream of which the extreme sea levels from this project should not be used.

Note 1

Extreme sea levels are considered accurate to one decimal place

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 but do not account for any local increase in sea level that may be induced by onshore wave action. Wave set-up, so called, would need to be estimated separately.

Note 3

Definition of annual exceedance probability

Annual exceedence probabilities (AEP) describe the likelihood of being exceeded in any given year. AEPs can also be expressed as chance. For instance, an AEP of one per cent has a chance of being exceeded of one in 100 in any given year. In coastal design this often termed ‘return period’.

Note 4

How to obtain the data

The data produced by this project can be obtained under licence via the Environment Agency Customer Contact Centre (www.environment-agency.gov.uk/contactus).

2 Data

2.1 Sources

Data used for the analysis and validation of results came from the following sources:

- Records from the UK National Network of Tide Gauges (often referred to as the 'Class A' tide gauge network, now used to describe these gauges in this report) run by the Tide Gauge Inspectorate at the National Tidal and Sea Level Facility.
- Gauge data supplied by the Environment Agency for this project.
- Gauge data supplied by the Scottish Environment Protection Agency for this project.
- Third party tide gauge data, kindly supplied by the following organisations:
    - Associated British Ports
    - British Oceanographic Data Centre, part of the Proudman Oceanographic Laboratory
    - Falmouth Harbour Commissioners
    - Port of London Authority
    - UK Dredging.
- Mean high water spring tide levels from Admiralty Tide Tables.
- Mean high water spring tide levels from POLTIPS3.

Appendix 1 contains a list of all tide gauge data used, its ownership and the data coverage. **Figure 2.1** shows the locations of all sites for which tide gauge data was obtained. **Appendix 2** contains a schedule of datums and high events at primary and validation gauge sites.

For validation purposes, reference was also made to reports containing information on notable historic events, such as the coast tidal flooding of 1953[3] along the east coast.

2.2 Data Review

The British Oceanographic Data Centre (BODC) is responsible for remote monitoring and retrieval of sea level data from the UK National Network on behalf of the National Tidal and Sea Level Facility (NTSLF). Daily checks are kept on the performance of the gauges and the data are downloaded weekly. These are then routinely processed and quality controlled prior to being made available for scientific use. Annual datasets were plotted and reviewed as a final check by Royal Haskoning.

All non-Class A tide gauge data made available for this project was supplied to the BODC to perform checks similar to those undertaken for the 'Class A' sites. A flag was assigned to suspect and missing data. A number of high tide values were rejected as erroneous through this process.

Further checks were done by Royal Haskoning to determine the suitability of this data for validation and as a guide for others when deciding whether to use this data in future studies. Time-series data (for example, levels at 15-minute intervals) of individual tide levels (annual maximum) were first examined to check that they were reliable and were not a spurious data point within the general sequence of tide levels.

The gauge data review was made by plotting each year's data as a level/time graph, then inspecting the graph for flaws such as:

- missing data;
- ‘spikes’, where the gauge is recording erroneously high levels;
- datum shifts, where the datum suddenly moves from one level to another;
- datum drift, where the datum shows an apparent general trend up and down through the year.

The quality of the non-Class A tide gauge data is summarised in **Appendix 1**. The summary includes a schedule assigning each year’s data to one of four quality classes, from “no data” to “good”.

2.3 Model data

Alongside tide gauge data, we used the Proudman Oceanographic Laboratory (POL) operational continental shelf tide-surge (CSX3) model at 12-km resolution to produce synthetic data from which the full suite of extreme sea level values was calculated.

This model is forced by the European Centre for Medium-Range Weather Forecasts ERA40 meteorological reanalysis. The dataset is based on a reanalysis and interpolation of meteorological data for the 45-year period between September 1957 and August 2002. Surface boundary conditions are the mean sea level atmospheric pressure and 10-m contour wind components derived from the ERA40 dataset. Tidal input at the model open boundaries consists of the largest 26 tidal constituents.

The fixed bed bathymetry used for the operational model use the digital Generalised Bathymetry Chart of the Oceans (GEBCO) data, and is maintained by BODC on behalf of the International Hydrographic Organisation (IHO) and the Intergovernmental Oceanographic Commission (IOC) of United Nations Educational Scientific and Cultural Organisation (UNESCO). Higher resolution bathymetry datasets have been incorporated into the GEBCO dataset by BODC.

A separate, higher resolution model was used here to produce results for the area within the North East Irish Sea (NEIS). This region is characterised by areas of tidal flats that dry out at low tide. The higher resolution model was used to represent the localised wetting and drying processes more accurately than POL’s larger 12-km resolution model. This model, run by JBA Consulting, is a 2D depth-average version of the Princeton Ocean Model. Like the POL model it is driven by ERA40 surface meteorology. It performs calculations on a grid which has a resolution of approximately 200-m at the coastline. It is forced at the ocean boundary by the tide and surge components from a coarser resolution model of the continental shelf that is of similar design to the POL 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 inter-tidal areas (that were dry during data acquisition).

Figure 2.2 shows locations of model points for both models employed for this project. Further details of the modelling can be found in **Appendix 3** and **Appendix 4**.

The model results were used to aid interpolation of sea level values between those calculated for the primary data points. Since the modelling took into account the varying tidal dynamics around the coastline, this means of interpolation was preferred to one based solely on relative distance. Further details are given later in this report.

3 Method of deriving extreme sea levels

3.1 Introduction

This section provides an overview of the methods used to derive extreme sea levels around the UK coast. A more detailed description of the methodology is given in **Appendix 3**.

The challenge of this project was to estimate sea levels which might occur for return periods considerably greater than the length of dataset on which these estimates are based.

Given the relative shortage of data, it is necessary to use statistical analysis to derive estimates of extreme sea levels. For example, for a sequence of water levels, the maximum value over this period can be seen from the data. If the exact statistical behaviour of these values is known, the corresponding value of the absolute maximum sea level can be calculated exactly. In practice the behaviour of values in a sequence is unknown, that is, they haven’t yet been observed, and therefore exact calculation of an absolute maximum sea level is impossible. However, suitable assumptions and detailed limit arguments can be applied, leading to a family of statistical models.

We need to be aware of the limitations in using statistical models to extrapolate to higher return periods than observed in a range of data. Two limitations are particularly pertinent. Firstly, the statistical expressions with the model, although well justified, remain theoretical so they may not fully and accurately cover the distribution in values that could arise over a very long time frame. Secondly, the results from the statistical model, as with other models, depend on the quality and quantity of the data inputs.

Overall therefore, we cannot say the results from this project are wholly accurate and will remain valid for all time. Nevertheless, they are derived from the best available data using the best available techniques. Their derivation has involved careful thought, intelligently applied, in conjunction with the mathematical analyses. As such, the results should be as sound as is reasonably possible at the present time. It would be prudent to review the findings in the future when more tide level data becomes available. An update every five years or so is recommended, assuming that additional data collected during this time is of sufficient quality.

3.2 Overview

The foundation of our analysis was tide level data as recorded at the 40 Class A gauge sites within the study area, together with equivalent data from five other sites. We accepted data from these other sites as suitable for inclusion in the primary data because the records were of suitable quality and covered an adequate record period. Importantly, the added sites provided information for locations not well represented by the Class A tide gauge coverage (such as Exmouth, Padstow and Moray Firth), and for places where further information was thought useful to properly represent tidal conditions in the area (Hilbre Island for Liverpool Bay, Southend for the Thames Estuary).

Data from the Class A gauge at Harwich was not used because, with its estuary location, the tidal values could be misleading for the intended coastal analysis.

The gauge sites used for primary data are shown on **Figure 3.1**.

Statistical analysis was undertaken for the Class A sites, and for the other five sites we included as primary sites, to generate probabilities of predicted high tide and of skew surge. Combining these two elements gave the overall extreme sea level probabilities, expressed here in terms of levels attributed to their respective average return period. This analysis used the **skew surge joint probability method (SSJPM)**, discussed in more detail later in this chapter.

For some sites it was necessary to apply some statistical smoothing to the growth in sea level with return period. Smoothing was done using data from neighbouring sites, a common approach used in extremes science to balance spatial variations of estimates. The decision to use smoothing was based on the shape of the growth curve from low to high return period sea levels, aiming to avoid implausibly steep or flat growth compared to other sites. It was also based on whether the SSJPM results alone, or results from spatial smoothing, better reflected the observed data as indicated by the occurrence frequency of annual maxima and notable high levels.

In order to provide complete coverage of return period sea levels around the coastline, and given that using all tide gauge data around the country would be a lengthy exercise, an interpolation method was used to determine return period sea levels at points between the primary sites. The process was assisted by use of results from the continental shelf tide-surge model and higher resolution North East Irish Sea model introduced earlier in this report. The modelling provided return period water levels for output model nodes located around the UK coastline. These nodes are presented in **Figure 2.2.**

The model results could not be used directly, but required a series of corrections to obtain extreme sea levels validated to gauge data. As a first step, the model results for nodes at the primary gauge data sites were corrected to accord with values obtained from statistical analysis of gauge records. Secondly, the model results for intermediate nodes were adjusted in line with the corrections made at the primary data sites. Thirdly, linear interpolation between model nodes was used to give return period sea level values at about two-km spacing along a nominal coastal chainage line. This linear interpolation, guided by the concept of sea levels varying smoothly around the coastline, involved smoothing using the relationship between the mean high water spring (MHWS) and one-year level and subsequent growth to higher return periods at the model points.

Finally, a further check was done to ensure the return period levels were plausible. This involved comparing extreme sea levels along the coastal chainage line with the apparent return period of high levels as indicated by the secondary tide gauge data, being all the data other than that used for the primary analysis. Where inconsistencies arose, the one-year level was further corrected to give a result more plausibly matching the secondary tide gauge data. One-year level values along the chainage line each side of the correction reference point were also adjusted to avoid “steps” or “spikes” in the progression of levels around the coast. These adjustments were generally across a distance encompassing four model nodes. The original growth in level to longer return periods was retained.

The validated values are given as the extreme sea level results from the project.

3.3 Skew surge

The approach used to derive extreme sea levels around the coastline is the skew surge joint probability method (SSJPM).

Surge arises when the atmospheric pressure changes, affecting the level of the water surface. Low sea surface pressure acts to raise the level, high surface pressure depresses it. Surface winds drive currents that also determine sea levels. For example, an offshore wind blowing towards land will drive water towards the coastline, leading to a rise in local sea level. The impact on sea level caused by these processes is referred to as surge, and can increase or decrease sea levels. As meteorological processes are independent of tidal forces, their influence can occur at any stage of the tide.

Skew surge is the difference between the predicted astronomical high tide and nearest experienced high water, as shown in **Figure 3.2**. The use of skew surge removes all phase differences (timing differences) between predicted and observed data.

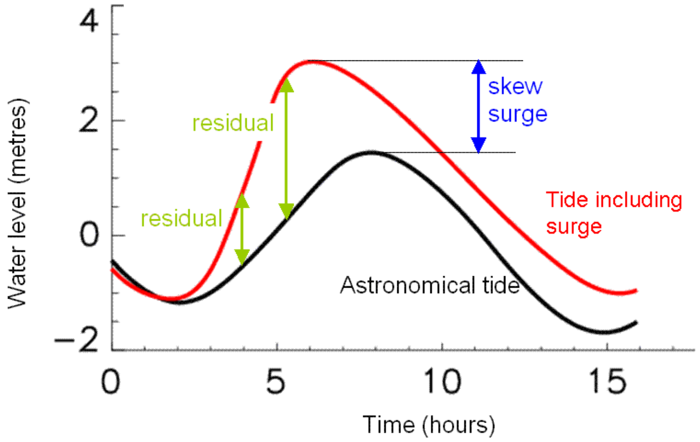

Figure 3.2: Illustration of the skew surge

‘Illusory’ surge residuals can often occur due to this phase difference, especially at the mid-tide stage. This is illustrated by **Figure 3.3** which shows how an “illusory” surge residual is created merely by the observed tide occurring slightly earlier than predicted, due to meteorological influence or tide gauge timing errors. For this reason, surge residuals seen in the mid-tide range are an unreliable indicator of the peak high water that will be attained. Their use in other analyses should be treated with caution.

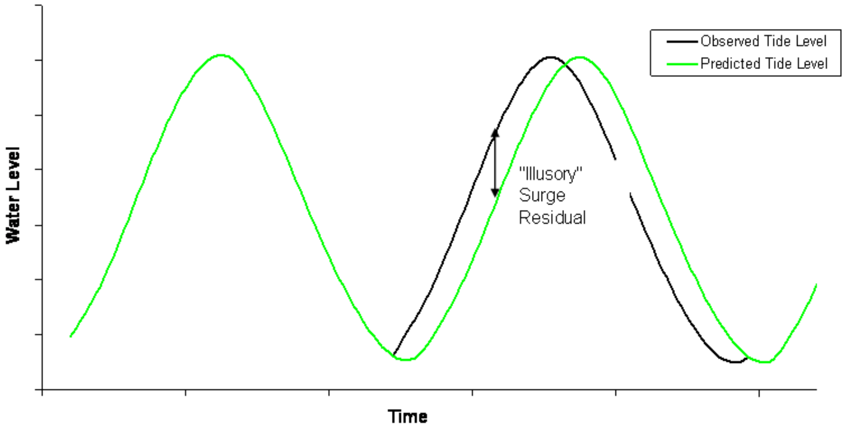

Figure 3.3 Illusory surge residual

3.4 Application of the SSJPM for the coastline

Statistical analysis was undertaken using the SSJPM for 40 Class A sites and the five supplementary primary sites. The latter are listed in **Table 3.1** together with the reasons for their inclusion.

Table 3.1 – Supplementary sites

Site	Reason for inclusion
Padstow	No Class A gauge between Newlyn and Ilfracombe. Data was of sufficient quality to apply SSJPM method.
Hilbre Island	Hilbre Island used because Liverpool Gladstone Dock gauge not used in the interpolation process (see Section 3.7.3). Hilbre Island of sufficient quality and length to apply SSJPM method.
Moray Firth	Historically a Class A site, therefore good quality data to apply SSJPM method.
Southend	Provides a long record to supplement information for the Thames Estuary. Sufficient quality and length to apply SSJPM methods.
Exmouth	Provides information for Lyme Bay, not well represented by the Class A network. Sufficient quality and length of data to apply SSJPM method.

All data was de-trended, using a historic sea level rise rate of two mm per year at each gauge, to a base year of 2008. The rate used was the net combination of land movement and changes in water level. Analysis by the NTSLF shows this historic rise to be common around the UK coast. Therefore, the results are consistent for all years and independent of sea level rise.

The peak high water levels for each observed tidal event were identified and the nearest predicted high tide selected. The difference between the two is known as the skew surge as shown in **Figure 3.2**. This process was repeated for all high water events for each year of data. As the semi-diurnal tidal period is 12.42 hours, this leads to approximately 705 values of skew surge with corresponding peak predicted tide each year.

In order to generate the probability distributions for skew surge and predicted high tide, histograms of the frequency of the data were first calculated. The probability density function is derived from the histogram of values by dividing by the total number of observations, in effect producing a distribution curve through the data values, as shown in **Figure 3.4**. By their nature, observations of extreme values are rare. Consequently, the tails of the probability density function for skew surge can be poorly defined. The general trend is for the number of positive skew surge observations to decrease with increasing skew surge value. The shortage in number of observations means this trend can be irregular. This irregular behaviour is transferred to the probability density function and can distort the distribution curve.

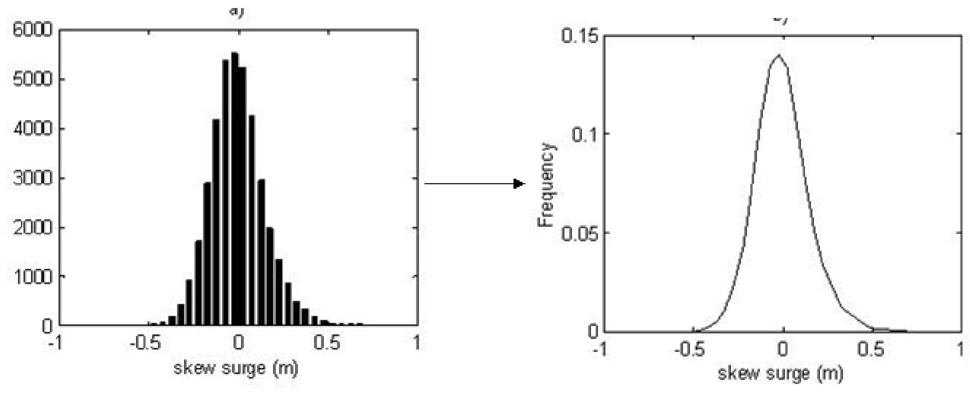

Figure 3.4 Smoothing the skew surge histogram

Here, a statistical model was used to fit a smooth upper tail to the probability density function. The statistical model used was the Generalised Pareto Distribution (GPD). The parameters in the GPD were set to give the best smoothed fit to the extreme value skew surges above a specific threshold level. **Figure 3.6** shows a schematic of the GPD, with all data above a given threshold defined by the statistical distribution.

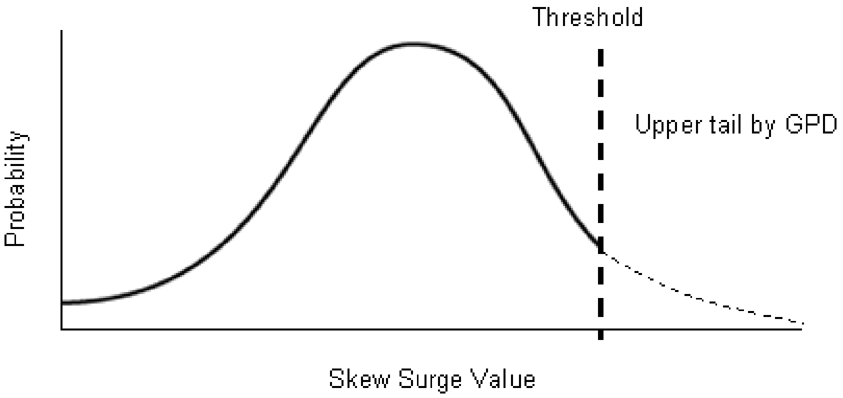

Figure 3.5 Schematic of the Generalised Pareto Statistical Distribution

Our basis for selecting the Generalised Pareto Distribution is that it is mathematically justified by asymptotic theory, is stable in form to the threshold choice for large enough thresholds, and has been found to provide an excellent fit to a range of oceanographic extremes in applications to wave heights, wave impacts, surge levels and current speeds [see Davison and Smith (1990)[4] and Coles (2001)[5]].

We recognise that there is an upper limit to the amount of surge which can possibly occur. The uncertainty surrounding definition of the maximum surge, although having a physically sound basis, would be an arbitrary decision. In view of this, we did not impose any capping on skew surge values within the GPD analysis.

Unlike storm surge levels, peak tide levels due solely to astronomical tidal forcing are deterministic and have a known absolute maximum. The distribution of peak tide levels therefore exhibits well-resolved tails and there is no requirement to fit a GPD for increased resolution.

For each gauge site, the lunar nodal cycle of high tides was derived from harmonic constituents. This cycle has an approximate period of 18.6 years, caused by the precession of the plane of the lunar orbit. Changes by this variation in lunar declination can alter the range of the tide by ±3.7 per cent when the declination amplitudes are greatest.

Joint probability analysis was used to form a probability distribution of all possible total sea levels from the skew surge distribution (with GPD tail fit) and peak tide levels from the full nodal cycle. Here, our joint probability analysis assumed independence between skew surge and peak tide levels; a test made in this project showed this assumption to be valid.

The duration of storm surges can encompass multiple high tides. This means that there may be a degree of dependence between extreme skew surge levels in the tide gauge record, for example two extreme skew surge level observations may have occurred during the same storm. A correction factor was derived to account for this dependence in the calculation of return period.

The final stage of the SSJPM method was expression of the probability distribution of total sea levels in terms of return periods. **Appendix 3** contains details of this process.

3.5 Adjustments to the SSJPM

3.5.1 Smoothing of the GPD tail parameters

For some sites the “raw” SSJPM results gave a growth in sea level with return period implausibly different to the growth seen elsewhere along that part of the coast. Examples to illustrate this are at Hinkley Point (implausibly high growth) and Portsmouth (unduly low growth), shown in **Figure 3.6** and **Figure 3.7** respectively. In these instances, statistical smoothing of the GPD “shape” parameter was applied.

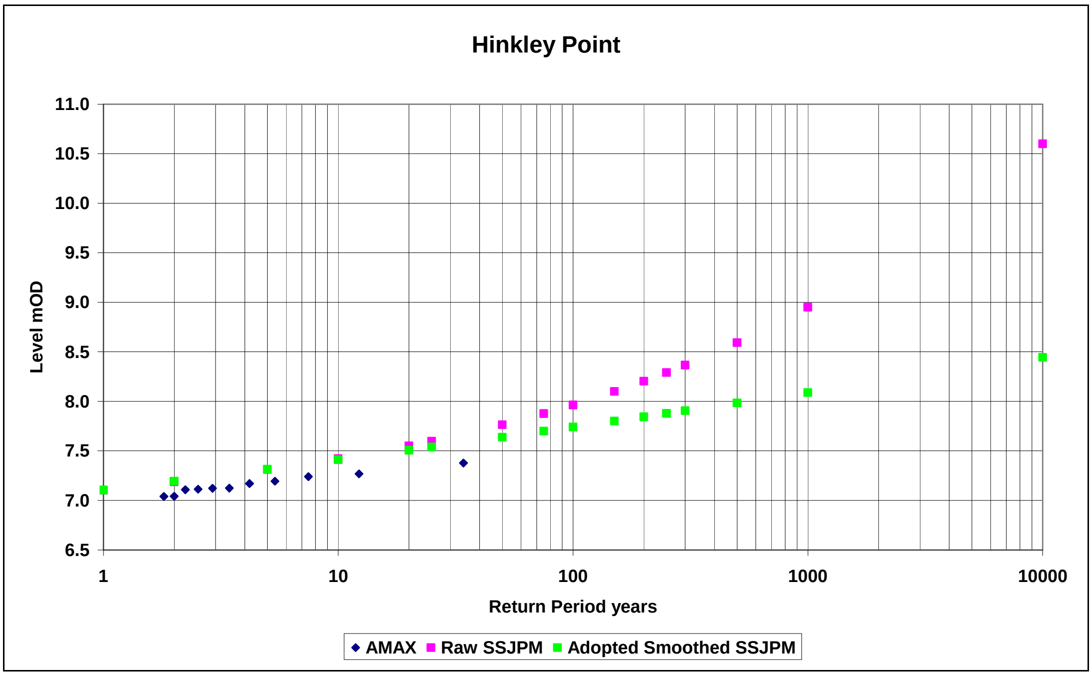

Figure 3.6 Implausibly high growth curve from ‘raw’ SSJPM results at Hinkley

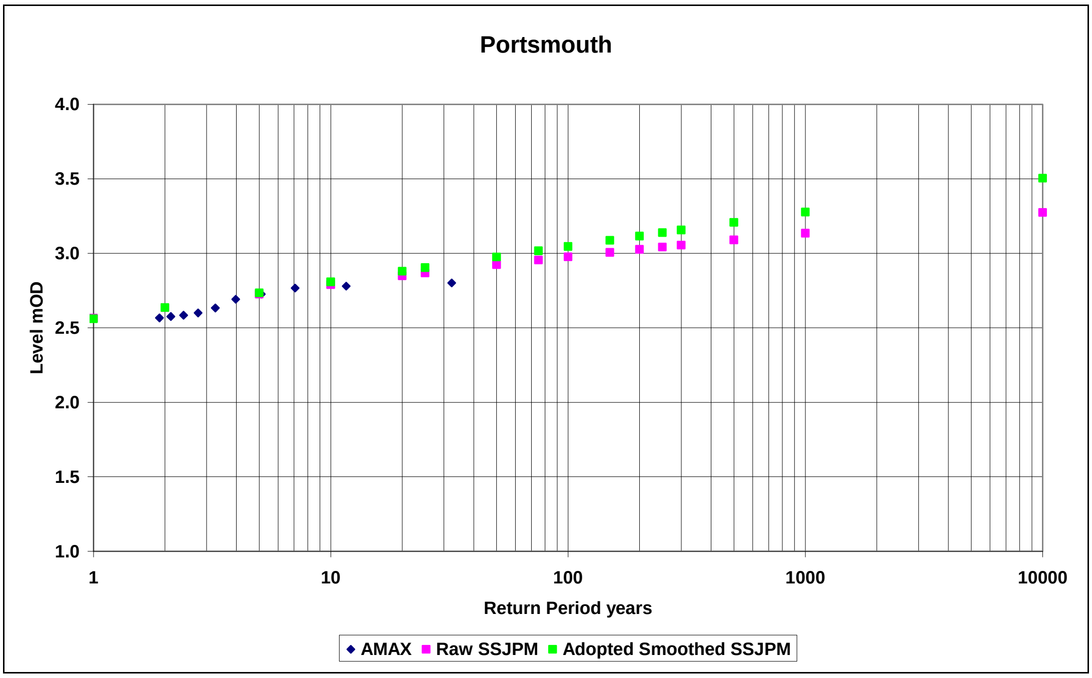

Figure 3.7 Dangerously low growth curve from raw’ SSJPM results at Portsmouth

Smoothing brought in parameters from four sites either side of the place in question, although a geographical cut-off was also applied. For the latter, parameters from sites along the English Channel were not allowed to influence those along the North Sea, and vice versa; likewise parameters from sites in the approaches to the Severn Estuary were not allowed to influence those on the open coast and parameters from sites in Western Scotland were not allowed to influence smoothing on Scotland's east coast. The smoothing sites were weighted according to the data length, therefore giving more credence to longer records. The sites where statistical smoothing was applied are noted in **Appendix 5**.

Smoothing based on location is used in many areas of extremes and has been found to work well at balancing spatial variation with statistical noise in estimates. The smoothing method used provided a consistent alternative to the 'raw' SSJPM where growth curves to higher return periods appeared physically implausible. Comparing the results of the SSJPM method alone with spatial smoothing, incorporating the statistical parameters of neighbouring primary sites, we assigned the most appropriate technique to give a physically plausible answer combined with a good match to observed data at the primary sites.

3.5.2 Sheerness

Discrepancies were identified between the Southend and Sheerness level values given by the SSJPM. We analysed event data from both sites to identify whether the difference between these levels was reflected in the observed data. This showed the real differences to be negligible. The results for Southend, which has a much longer gauge record than at Sheerness, were the more plausible when compared to the gauge observations. Therefore, Southend levels were also applied for Sheerness.

3.5.3 Lowestoft

Discrepancies in terms of the growth were also noted at Lowestoft compared to observed levels and return periods of known events, for example January 1953. This was the case for both the raw SSJPM results and those derived using neighbouring sites to smooth the GPD tail parameters. The one-year level using the SSJPM method matched well with the observed data, and so was retained.

Trend lines of sea levels (MHWS, one-year and 200-year) and growth from high probability (low return periods) to low probability (high return periods) were compared for neighbouring sites. The trend showed a tendency for a rise in the growth curve and decrease in tide level from the north and south, to converge at a chainage consistent with Lowestoft. Therefore, using the one-year SSJPM method as a base, growth to higher return periods was interpolated using the growth curve trend line from neighbouring sites.

3.6 Interpolation between primary sites

The statistical analysis provided estimates of return period sea levels at the Class A and other supplementary primary sites. In order to provide continuous coverage around the coastline, it was necessary to interpolate using results from these primary sites as the corrector.

We used numerical models as dynamic interpolators between the primary sites. It was important that extremes simulated by the numerical models were statistically consistent with those derived from observed time series at the same locations. The only practical way that numerical models can generate time series comparable to observations is by forcing the model's surface boundary condition with weather inputs from long meteorological re-analyses. **Appendix 4** contains details of the numerical models.

The raw model results were lower (this difference varied between primary sites) at the primary sites compared to the observed data at these locations. Numerical models of tides all consistently underestimate the largest amplitude tides, compared to tide gauge observations. Certain higher frequency tidal components present in an observational record are not reproduced in numerical models. Furthermore, the prescribed friction that ensures the computer model simulates the tidal wave accurately at the basin-scale has the effect of damping tidal response in very shallow water (where the gauge is).

Therefore, corrections were applied for levels at these sites. Extreme sea level values for the model nodes closest to the primary sites were corrected to accord with those given by the SSJPM statistical analysis.

The models provided return period extreme sea levels at intermediate points between primary sites broadly at 12-km spacing, though at a finer resolution in the North East Irish Sea. At these sites, the model results were corrected according to a proportional difference in model variations and observed data at the primary sites. The idea of this smoothing was to take advantage of the change in physical tidal processes around the coast. In principle, these changes would be represented by the numerical modelling. This method was preferred to interpolating by distance, which would not reflect the physical processes.

3.7 Coastal trend line

3.7.1 Coastal chainage

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 distances would not become unduly distorted by small coves and promontories, as would be the case if mean low water mark was used, for example. Chainage points were set at two-km intervals. The trend line is shown on **Figure 1.1** to **Figure 1.6**.

3.7.2 Interpolation between adjusted points

The corrected model node sea level values, as noted in **Section 3.6**, were applied to their respective nearest coastal chainage points. An interpolation was then made between these adjusted points, using the trend in relationship between the MHWS and model one-year level to guide the one-year values. The subsequent growth to higher return periods was taken as varying linearly between the adjusted model points.

3.7.3 Trend line at Liverpool Bay

The trending using the Liverpool smoothed SSJPM results did not match the adjacent coastal chainages despite matching well with observed data. Therefore, standalone values based on the SSJPM analysis were provided for Liverpool. The Liverpool data was removed from the interpolation process between primary sites to ensure a smooth trend along the coast.

As a result, statistical analysis was undertaken using data from Hilbre Island. The growth curve derived by statistical analysis at Hilbre Island matched well with observed data and was deemed a good substitute for the Liverpool gauge data in the interpolation process.

Liverpool, Gladstone Dock extreme sea level values, based on SSJPM analysis, are included in **Table 3.2**. These values only apply for Liverpool and are not included in the GIS Shapefile of the coastal chainage line.

Table 3.2 – SSJPM results for Liverpool, Gladstone Dock

Return Period (years)	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Sea Level (mOD)	5.51	5.62	5.77	5.90	6.04	6.09	6.25	6.35	6.42	6.52	6.60	6.67	6.72	6.87	7.09	7.96

3.8 Adjustments at intermediate model points

Tide gauge data was obtained for thirty-six sites (here termed the secondary sites) at intermediate locations between the primary sites; these are shown in **Figure 2.1**. Sea level values along the coastal chainage line, derived as in **Section 3.7**, were compared with event records from these secondary sites. The purpose of this comparison was to look for consistency between the corrected model output levels and intermediate observed levels using two criteria:

1. To identify how the lower end (below ten-year return period) compared with return periods implied by the data.
2. To identify, for widespread events, whether the return period of the event was broadly similar at the primary sites and the intermediate sites, for example the January 1953 event record at Wells.

For sites where these comparisons resulted in no obvious discrepancy, there was no basis to alter the intermediate values between the primary sites.

For sites where discrepancies were identified, comparative sea levels were obtained for a wide range of notable events as recorded at the secondary site and its surrounding primary sites. The sites where this was undertaken are listed below:

- Uphill
- Llanelli
- Fleetwood
- Ramsden Dock, Barrow
- Orkney Islands
- Burgh Sluice
- Wells
- Littlehampton
- Calshot
- Cowes
- Lymington

The aim of this comparison was to identify differences in peak tide levels for these notable events. From this, taking into account some variation, clear trends of a sea level relationship were identified between the secondary and primary sites for extreme events. The one-year level at the secondary site was made consistent with the primary site one-year level by adding or subtracting this ‘event difference’ relationship. Return periods of notable events became more consistent between adjacent sites and gave a better fit to observations at the secondary site and its surrounding primary sites. This method gave a more plausible trend of levels around the coast.

For sites where these further adjustments were applied, the growth curve given by the original trending was retained. The reason for this was that there was not enough observed data at the high end of the growth curve for these sites.

Where sea levels at the secondary sites were adjusted, values at nearby intermediate points between the primary sites also required adjustment to retain a sensible trend in levels along the coastline. This trend was the relationship between MHWS and the one-year level and gave a better fit to the observations at the secondary sites.

3.9 Confidence intervals

This project provides an assessment of uncertainty, in the form of confidence intervals, for all sites on the main coastal chainage. The 95 per cent confidence bounds were calculated for sites where SSJPM statistical analysis was run, excluding sites where statistical smoothing was employed. It was not possible to statistically determine the confidence bounds at these latter sites.

Confidence bounds were used as the starting point to develop empirical confidence intervals for all output points along the main chainage. The approach was guided by the need to be precautionary, given the uncertainties, and the need to be consistent around the coast, mindful of the geography. In this project we took confidence intervals to be half of the confidence bound width and expressed as a distance (±) from the mean sea level estimate.

Confidence intervals for raw SSJPM analysis sites were applied to all output points 50 km either side of the site. This 50-km buffer was geographically constrained at boundaries between different sea, for example the English Channel and St George's Channel; Atlantic Ocean and North Sea; and North Sea and English Channel.

Outside of the 50-km buffer, a further addition was applied, increasing the confidence interval. This empirical approach was necessary in the absence of statistical analysis at intermediate sites.

We have also provided confidence intervals for the Scottish Islands. In the absence of uncertainty information for a fixed point on some islands, we adopted an empirical approach to provide confidence intervals. This approach used uncertainty information from the main chainage and made an additional allowance for the islands. This approach was used for the western isles, including Islay and Jura. This approach was also used for the Orkney Islands.

We used the same information to derive extreme sea levels for the Isle of Arran to that of the main chainage along the Ayrshire and Argyll coastlines. We have therefore taken the same approach to derive confidence intervals for the Isle of Arran.

For the Outer Hebrides we calculated confidence intervals for Stornaway. We have therefore adopted the same approach as the main chainage, with points within 50 km of Stornaway having the same confidence intervals. Outside of this, an additional allowance was made where there was increased uncertainty. Furthermore, we included an additional uncertainty allowance for the western Outer Hebrides. This coastline is very different to that at Stornaway, therefore we can expect the uncertainty to be slightly greater for these points.

Appendix 6 contains further details of the derivation of confidence intervals.

We have provided confidence intervals for the Shetland Islands at Lerwick only.

3.10 Derivation of standard surge shapes

This project also provides surge shapes to derive appropriate total tide curves. For the occurrence of an extreme tide level, the total tide curve will be the combination of underlying astronomical tide with a storm surge. The storm surge can be represented by a shape defining the increase and decline of surge over time.

In reality, surge shapes are highly variable between different extreme events. However, for practical purposes 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. It is recognised that the surge shape may vary between different sections of the coast.

In creating standard surge shapes we were mindful of their probable applications. We therefore sought to identify shapes which, when used to create total event tide curves, would lead to a fairly precautionary assessment of potential flood risk but without being unduly conservative in this respect.

Standard surge shapes were derived by examining the skew surge as recorded at the Class A tide gauge sites in England, Wales and Scotland. More particularly, for each site the fifteen largest skew surge events were identified. The variation in surge with time was plotted for each event. Ignoring some events which were potentially misleading for this exercise, the surge time plots were then standardised to a unit height and compared.

Since we sought a precautionary yet sensible standard surge shape, we found this by a process we called “time-integrated duration”. To generate this type of surge, the duration of each of the 15 event surges at particular levels was first calculated. Out of the 15 event surges, the maximum duration at each level in the surge column was then determined. Maximum durations were then arranged to form the design 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.

Full details of the derivation are given in **Appendix 7.**

4 Results and discussion

4.1 Extreme sea levels

Extreme sea levels for annual exceedance probability ranging from 100 to 0.01 per cent (one to 10,000 year return periods) are provided in a Shapefile. **Table 4.1** presents a schedule of extreme sea levels calculated for the primary gauge sites.

The chainage given to coastal sites is based on an empirical nearshore reference line adopted for this project. The chainage is offset by two km from the coastline to ease viewing with mapping. The points represent a perpendicular coastal point. The starting point is at Newlyn, assigned chainage zero. The chainage line follows a clockwise direction around the coast of England, Wales and Scotland.

Additional chainages are provided for the following island groups:

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

Additional points are provided at the following sites:

- St Mary's (Isles of Scilly)
- Port Erin (Isle of Man)
- Lerwick (Shetland Islands).

Single points are provided for these islands.

All quoted levels are to a base date of 2008.

Note

Extreme sea levels are considered accurate to one decimal place

Extreme sea levels provided as part of 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.

4.2 Confidence in the results

Confidence intervals are provided in a Shapefile for all points on the main chainage and are discussed in **Appendix 6**. Confidence intervals are provided for all annual exceedance probabilities. The chainage mirrors that of the extreme sea levels and care should be taken to ensure the same chainage point is selected when choosing a sea level value and corresponding confidence interval.

Confidence intervals are given to one decimal place, as no greater accuracy is warranted.

4.3 Standard surge shapes

Surge shapes are provided in a spreadsheet for forty Class A sites around the UK. A Shapefile provides a reference for the surge shape to apply at the Class A sites as well as for a respective section of the coastline. Coverage encompasses 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 geographic bounds to apply these surge shapes are provided in **Appendix 7**.

Table 4.1		**Return period levels at primary sites (mOD except where stated)** **Note 1 – Levels referenced to Local Datum**															
Site	**Chainage (km)**	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Newlyn	0	3.06	3.12	3.21	3.27	3.33	3.35	3.41	3.44	3.46	3.49	3.51	3.53	3.54	3.58	3.63	3.78
St Mary's (Note 1)	N/A	3.40	3.46	3.54	3.59	3.64	3.66	3.70	3.73	3.75	3.78	3.79	3.81	3.82	3.85	3.90	4.04
Padstow	128	4.51	4.57	4.65	4.72	4.78	4.80	4.86	4.90	4.92	4.96	4.98	5.00	5.02	5.06	5.12	5.32
Ilfracombe	250	5.39	5.46	5.55	5.62	5.69	5.72	5.79	5.83	5.86	5.91	5.94	5.96	5.98	6.04	6.12	6.42
Hinkley Point	326	7.10	7.19	7.31	7.41	7.51	7.54	7.64	7.70	7.74	7.80	7.84	7.88	7.91	7.98	8.09	8.45
Avonmouth	380	8.16	8.27	8.43	8.55	8.67	8.72	8.85	8.92	8.98	9.06	9.11	9.16	9.19	9.29	9.43	9.89
Newport	398	7.54	7.64	7.78	7.89	8.00	8.04	8.16	8.23	8.28	8.35	8.41	8.45	8.48	8.58	8.72	9.22
Mumbles	492	5.47	5.54	5.65	5.74	5.83	5.86	5.95	6.01	6.05	6.11	6.15	6.18	6.21	6.28	6.39	6.77
Milford Haven	622	4.14	4.22	4.33	4.40	4.48	4.51	4.59	4.64	4.67	4.72	4.75	4.78	4.80	4.87	4.95	5.26
Fishguard	712	3.09	3.16	3.24	3.31	3.37	3.40	3.46	3.49	3.52	3.56	3.58	3.60	3.62	3.66	3.73	3.93
Barmouth	832	3.48	3.59	3.73	3.83	3.92	3.95	4.04	4.10	4.13	4.18	4.22	4.24	4.27	4.33	4.41	4.66
Holyhead	1,012	3.36	3.44	3.54	3.61	3.68	3.70	3.77	3.80	3.83	3.87	3.89	3.91	3.93	3.98	4.04	4.22
Llandudno	1,110	4.74	4.82	4.93	5.01	5.09	5.12	5.20	5.25	5.29	5.34	5.38	5.40	5.43	5.49	5.58	5.89
Hilbre Island	1,154	5.28	5.38	5.52	5.62	5.72	5.75	5.84	5.90	5.94	5.99	6.03	6.06	6.09	6.16	6.25	6.55
Port Erin (Note 1)	N/A	3.32	3.41	3.52	3.60	3.68	3.70	3.77	3.81	3.84	3.88	3.90	3.92	3.94	3.99	4.04	4.22
Heysham	1,254	5.89	6.01	6.17	6.29	6.42	6.45	6.58	6.65	6.70	6.77	6.82	6.86	6.89	6.98	7.09	7.48
Workington	1,390	5.10	5.21	5.35	5.46	5.56	5.60	5.70	5.76	5.81	5.87	5.91	5.94	5.97	6.04	6.15	6.47
Portpatrick	1,648	2.82	2.91	3.03	3.11	3.19	3.22	3.30	3.34	3.37	3.42	3.45	3.47	3.49	3.54	3.61	3.83
Millport	1,782	2.65	2.77	2.93	3.06	3.20	3.24	3.38	3.46	3.52	3.61	3.67	3.72	3.76	3.87	4.03	4.60
Port Ellen (Islay)	N/A	1.51	1.61	1.74	1.84	1.93	1.96	2.05	2.10	2.14	2.19	2.22	2.25	2.27	2.33	2.41	2.66
Tobermory	2,320	3.00	3.11	3.25	3.36	3.47	3.50	3.62	3.69	3.74	3.82	3.87	3.91	3.94	4.04	4.18	4.67
Ullapool	2,564	3.23	3.32	3.43	3.51	3.59	3.61	3.69	3.73	3.76	3.79	3.82	3.84	3.86	3.90	3.96	4.13
Stornoway (Note 1)	N/A	2.91	2.98	3.07	3.14	3.21	3.22	3.29	3.32	3.34	3.38	3.40	3.42	3.43	3.47	3.52	3.68
Kinlochbervie	2,670	3.19	3.28	3.41	3.51	3.61	3.64	3.74	3.80	3.84	3.90	3.94	3.97	4.00	4.07	4.17	4.51
Lerwick (Note 1)	N/A	1.52	1.57	1.64	1.69	1.73	1.75	1.79	1.81	1.83	1.85	1.87	1.88	1.89	1.92	1.95	2.06
Wick	2,870	2.41	2.48	2.56	2.63	2.69	2.71	2.77	2.81	2.83	2.87	2.89	2.91	2.93	2.97	3.03	3.24
Moray Firth	3,012	2.85	2.91	3.00	3.07	3.13	3.16	3.22	3.26	3.29	3.33	3.35	3.37	3.39	3.44	3.51	3.72
Aberdeen	3,226	2.68	2.75	2.84	2.91	2.97	2.99	3.05	3.09	3.11	3.14	3.17	3.18	3.20	3.24	3.29	3.45
Leith	3,420	3.37	3.44	3.54	3.61	3.69	3.72	3.80	3.85	3.88	3.94	3.97	4.00	4.03	4.10	4.20	4.57
North Shields	3,630	3.20	3.27	3.38	3.46	3.55	3.58	3.67	3.72	3.76	3.82	3.86	3.90	3.92	4.00	4.11	4.52

Table 4.1		Return period levels at primary sites (mOD except where stated) Note 1 – Levels referenced to Local Datum															
Site	**Chainage (km)**	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**
Whitby	3,720	3.37	3.46	3.58	3.68	3.78	3.81	3.92	3.98	4.02	4.09	4.14	4.17	4.20	4.29	4.41	4.83
Immingham	3,888	4.18	4.28	4.42	4.53	4.64	4.67	4.78	4.84	4.89	4.95	5.00	5.03	5.06	5.14	5.25	5.61
Cromer	4,096	3.14	3.26	3.43	3.56	3.71	3.76	3.92	4.01	4.08	4.18	4.25	4.31	4.36	4.50	4.69	5.42
Lowestoft	4,162	2.00	2.14	2.33	2.48	2.65	2.70	2.88	2.99	3.07	3.19	3.27	3.34	3.39	3.55	3.78	4.63
Felixstowe Pier	4,232	2.72	2.85	3.03	3.17	3.33	3.38	3.55	3.65	3.72	3.83	3.90	3.97	4.02	4.16	4.37	5.16
Southend	4,312	3.61	3.72	3.87	4.00	4.13	4.18	4.32	4.41	4.47	4.57	4.64	4.69	4.74	4.87	5.05	5.75
Sheerness	4,314	3.61	3.72	3.87	4.00	4.13	4.18	4.32	4.41	4.47	4.57	4.64	4.69	4.74	4.87	5.05	5.75
Dover	4,410	3.77	3.88	4.03	4.13	4.24	4.27	4.37	4.43	4.48	4.53	4.57	4.61	4.63	4.70	4.80	5.12
Newhaven	4,526	3.87	3.94	4.04	4.12	4.19	4.22	4.29	4.34	4.37	4.42	4.45	4.48	4.50	4.56	4.64	4.91
Portsmouth	4,616	2.56	2.64	2.73	2.81	2.88	2.90	2.98	3.02	3.05	3.09	3.12	3.14	3.16	3.21	3.28	3.50
Bournemouth	4,682	1.40	1.47	1.56	1.62	1.68	1.70	1.76	1.79	1.81	1.85	1.87	1.89	1.90	1.94	1.99	2.16
Weymouth	4,736	1.77	1.84	1.93	1.99	2.05	2.07	2.14	2.17	2.20	2.23	2.26	2.28	2.29	2.34	2.40	2.59
Exmouth	4,836	2.74	2.81	2.90	2.97	3.04	3.06	3.13	3.17	3.20	3.25	3.28	3.30	3.32	3.38	3.46	3.76
Devonport	4,950	2.94	3.01	3.10	3.17	3.24	3.26	3.33	3.36	3.39	3.43	3.46	3.48	3.49	3.54	3.60	3.81

5 Conclusions

We used the best available data and improved methods to generate validated statistical and modelled values for predicted extreme sea levels against separate gauge data. We have also provided full coverage for England, Scotland and Wales, including islands.

We that support be given to tide gauge operators in their management of the gauges to ensure high quality records are sustained. The datum of each gauge should be validated, using GPS surveying so levels accord with current national practice. The data from each gauge should be reviewed regularly, perhaps monthly, to identify whether recording defects are arising (apparent datum change, data gaps and other errors). If defects are seen, corrective action should be taken without delay.

Additional tide gauge data could be used in any future updates to this project, both in the statistical analysis and numerical modelling, at intermediate sites between the Class A network of tide gauges currently employed. A suggested timescale to update this project is five years. New data could be used to correct the one-year levels at intermediate model points and increase confidence in the interpolation using a numerical model.

Future similar projects would benefit from the development of operational numerical models in embayment and estuarine locations to increase the resolution and representation of physical processes at these locations. We used the JBA North East Irish Sea model which increases the coverage of model outputs in the North East Irish Sea (including Liverpool Bay, Morecambe Bay and the Solway Firth). Suggested locations for development of finer resolution models include the Solent, the Wash and the Severn Estuary. The development will not necessarily improve the reliability of the output, but the additional output points will be useful to improve interpolation.

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Key:

- - - - - Estuary Boundaries

▪ Coastal Chainage

■ Supplementary Gauges

● Class A Sites

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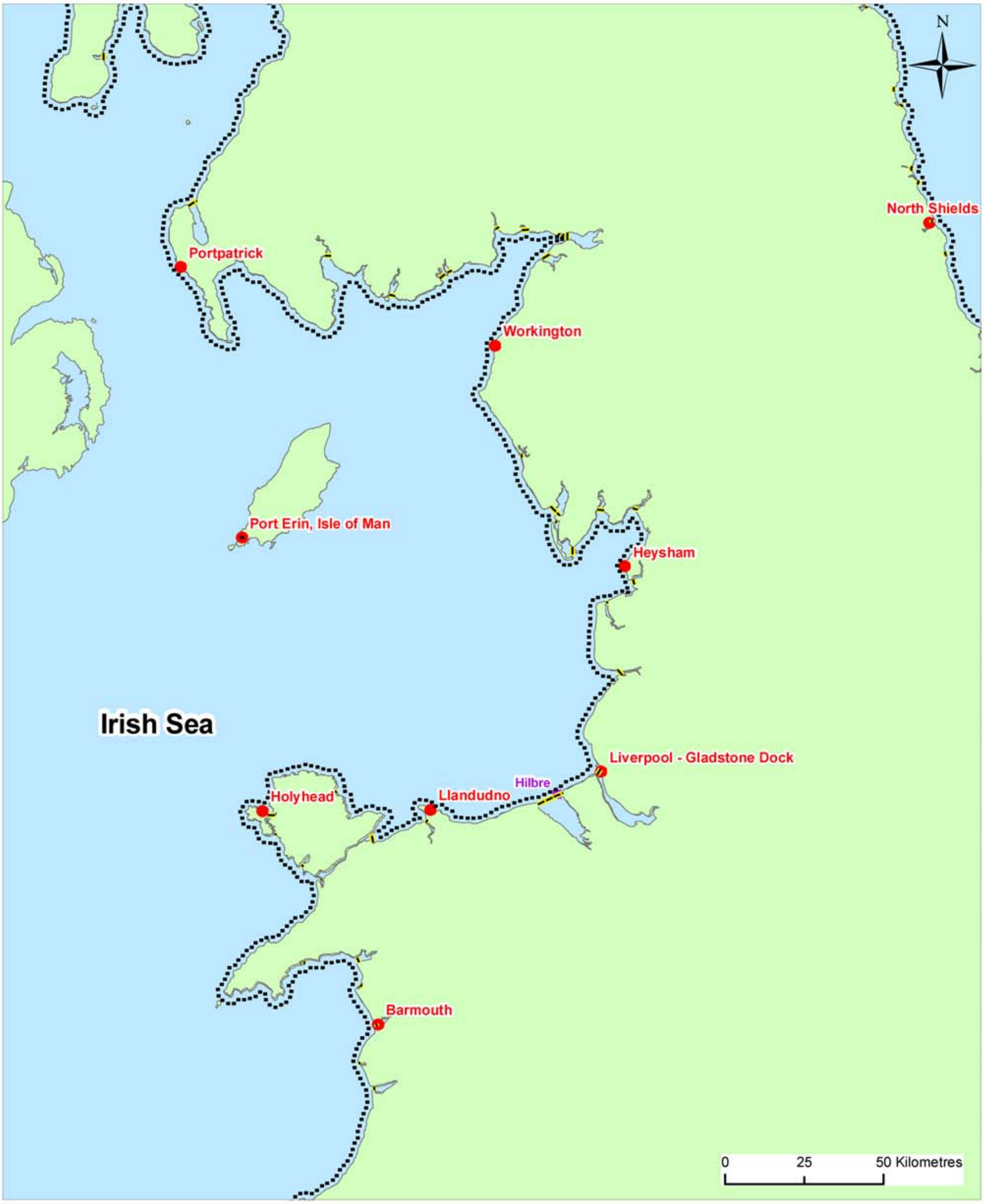

Key:

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- ----- Estuary Boundaries

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Date:
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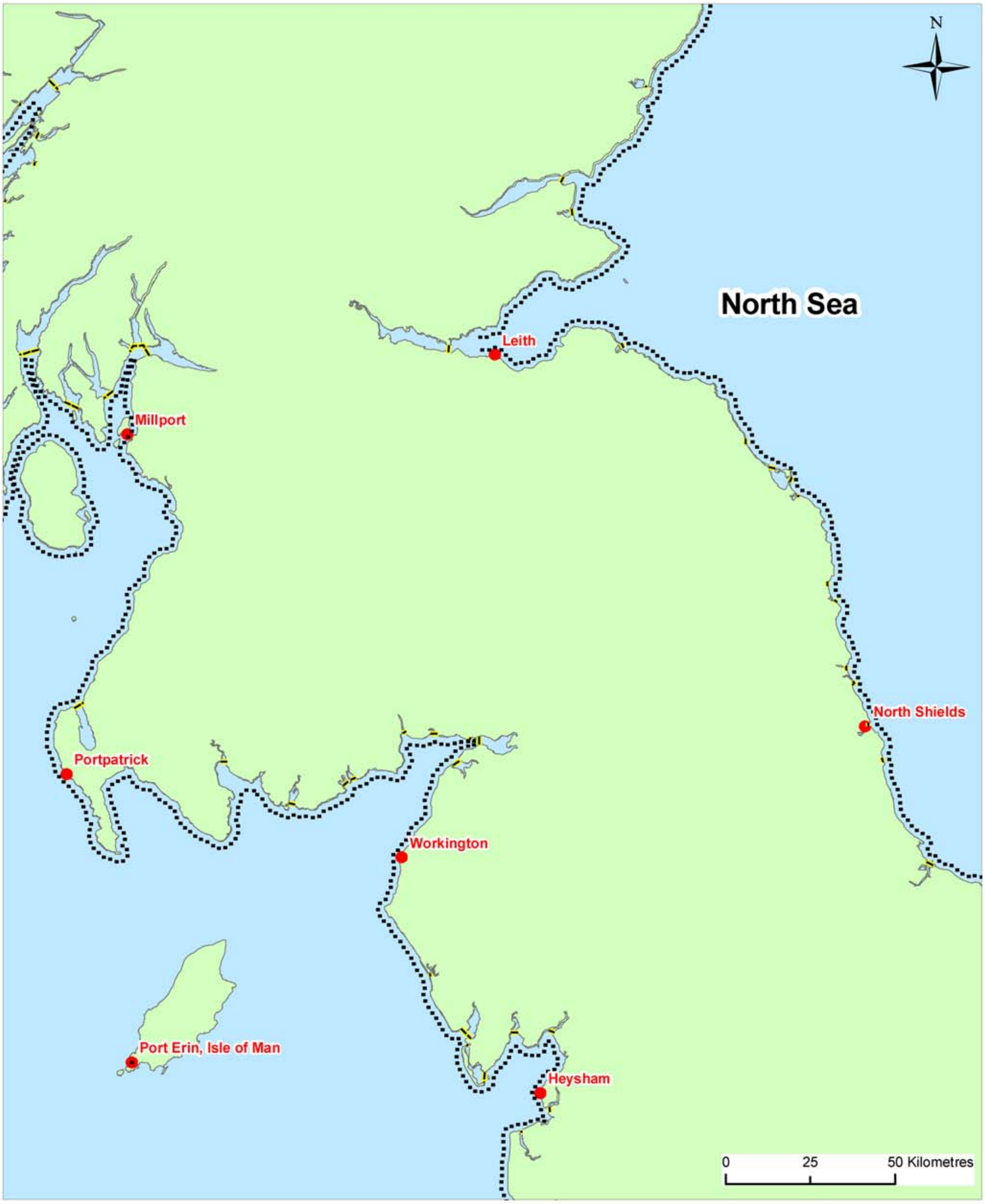

Key:

▪ Coastal Chainage
■ Supplementary Gauges
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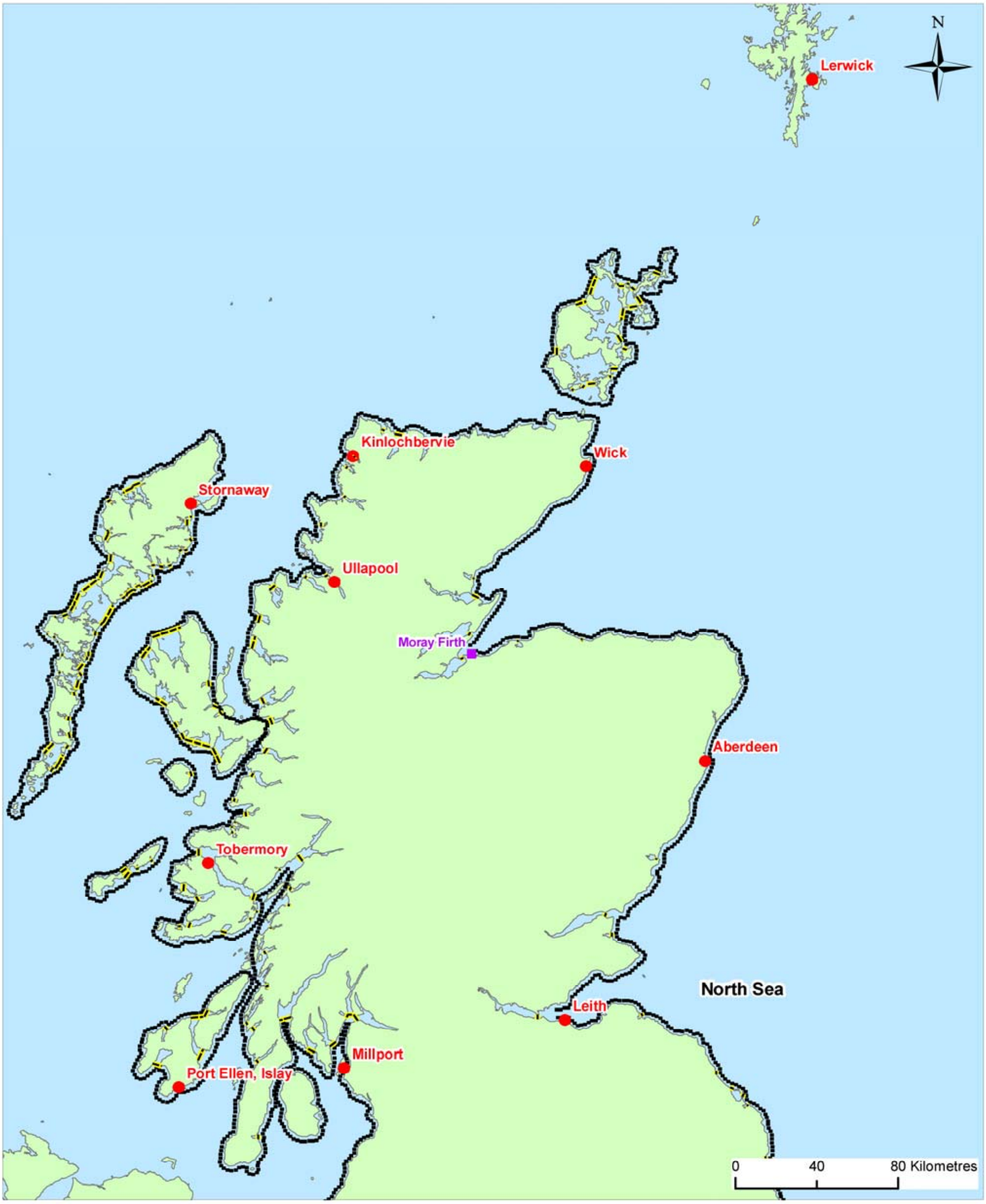

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- ----- Estuary Boundaries

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I:\9S7299\Technical_Data\F12_GIS\Projects\Report_Figures\Extreme_Sea_Levels

Title:
Study Area - Scotland

Project:
SC060064: Development and Dissemination of Coastal and Estuary Extremes

Client:
Environment Agency

Date:
2010

Scale @A4:
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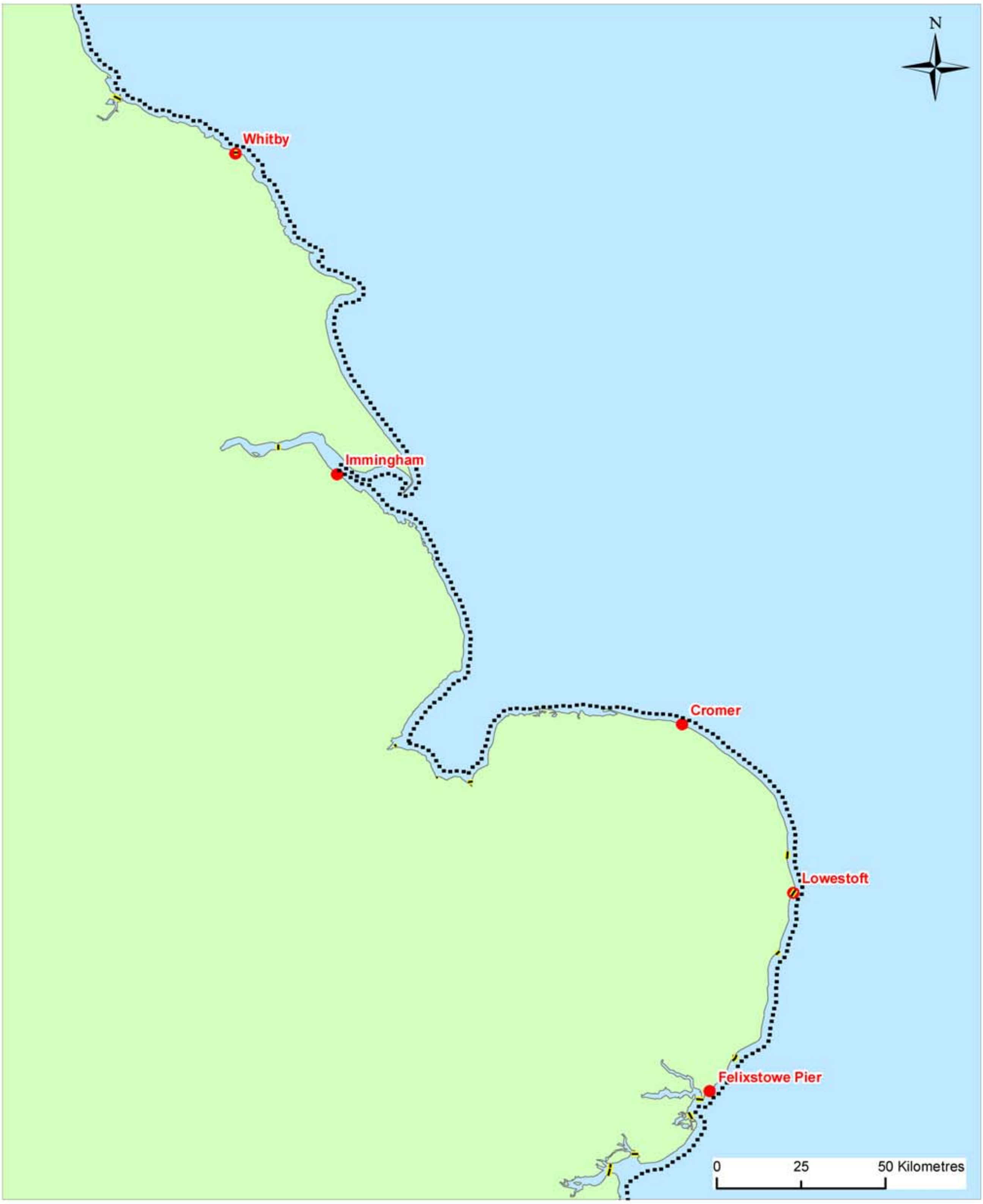
Figure:
1.4



Key:

▪ Coastal Chainage

■ Supplementary Gauges

● Class A Sites

----- Estuary Boundaries

Source / Copyright

I:\9S7299\Technical_Data\F12_GIS\Projects\Report_Figures\Extreme_Sea_Levels

Title:
Study Area - East

Project:
SC060064: Development and Dissemination of Coastal and Estuary Extremes

Client:
Environment Agency

Date:
2010

Scale @A4:
1:1,500,000

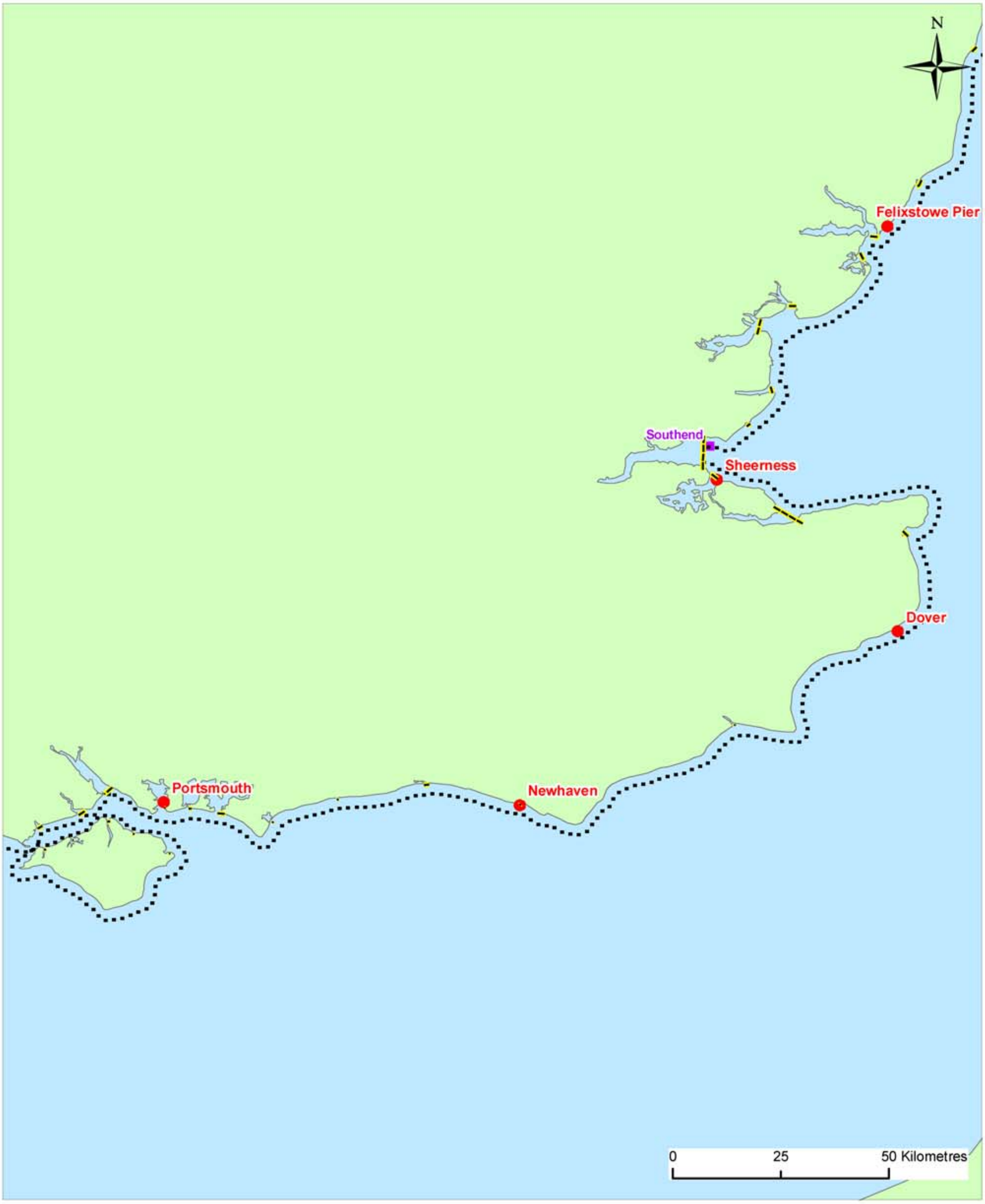
Figure:
1.5

defra Department for Environment Food and Rural Affairs

Environment Agency

ROYAL HASKONING

SEPA Scottish Environment Protection Agency



Key:

- ▬ ▬ Estuary Boundaries
- ▪ Coastal Chainage
- ■ Supplementary Gauges
- ● Class A Sites

Title:
Study Area - South East

Project:
SC060064: Development and Dissemination of Coastal and Estuary Extremes

Client:
Environment Agency

Date:
2010

Scale @A4:
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Figure:
1.6

Source / Copyright

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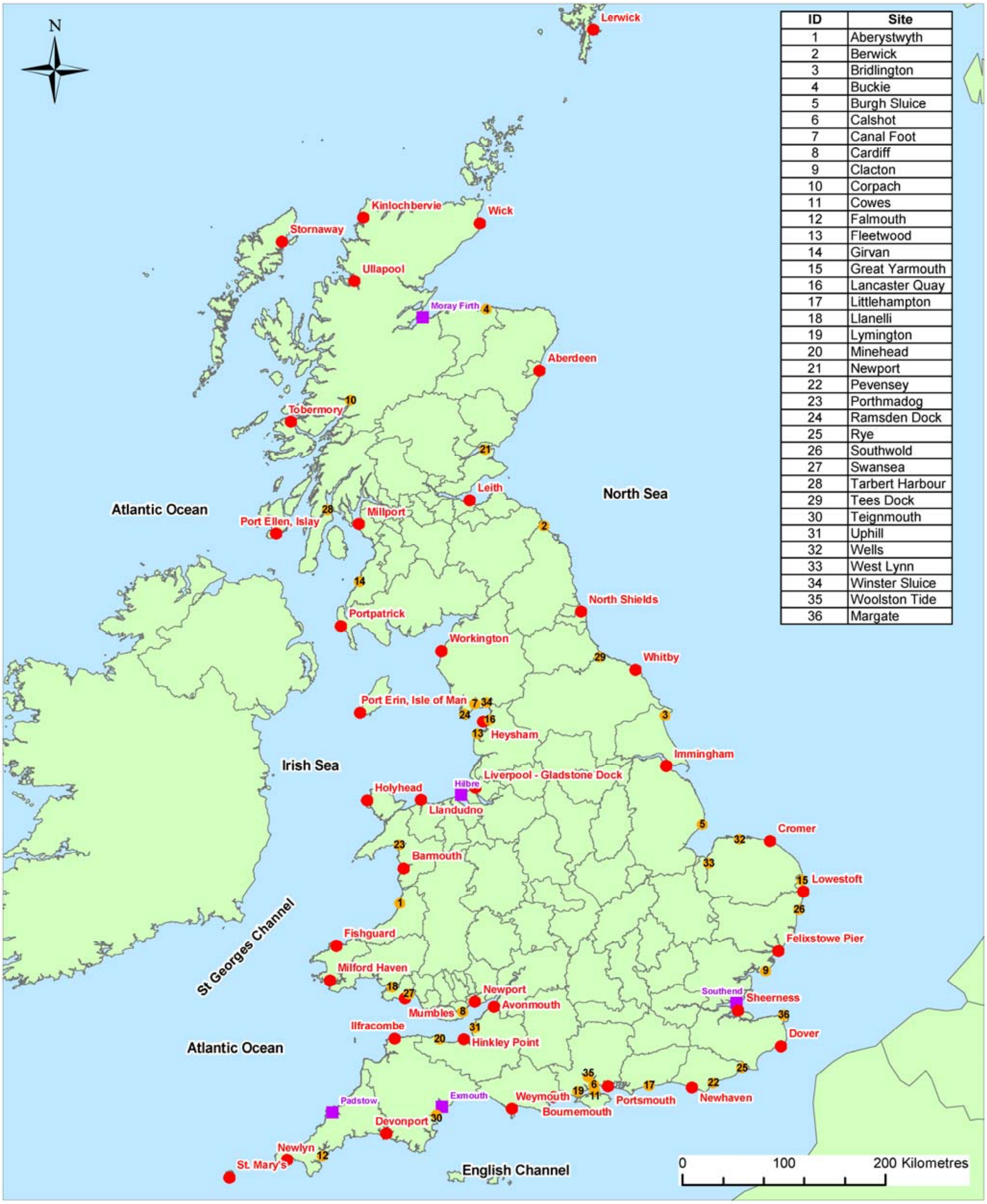


ID	Site
1	Aberystwyth
2	Berwick
3	Bridlington
4	Buckie
5	Burgh Sluice
6	Calshot
7	Canal Foot
8	Cardiff
9	Clacton
10	Corpach
11	Cowes
12	Falmouth
13	Fleetwood
14	Girvan
15	Great Yarmouth
16	Lancaster Quay
17	Littlehampton
18	Llanelli
19	Lymington
20	Minehead
21	Newport
22	Pevensey
23	Porthmadog
24	Ramsden Dock
25	Rye
26	Southwold
27	Swansea
28	Tarbert Harbour
29	Tees Dock
30	Teignmouth
31	Uphill
32	Wells
33	West Lynn
34	Winster Sluice
35	Woolston Tide
36	Margate

Key:

- ● Additional Gauge Sites
- ● Class A Sites
- ■ Supplementary Gauges

Title:
Tide Gauge Locations

Project:
SC060064: Development and Dissemination of Coastal and Estuary Extremes

Client:
Environment Agency

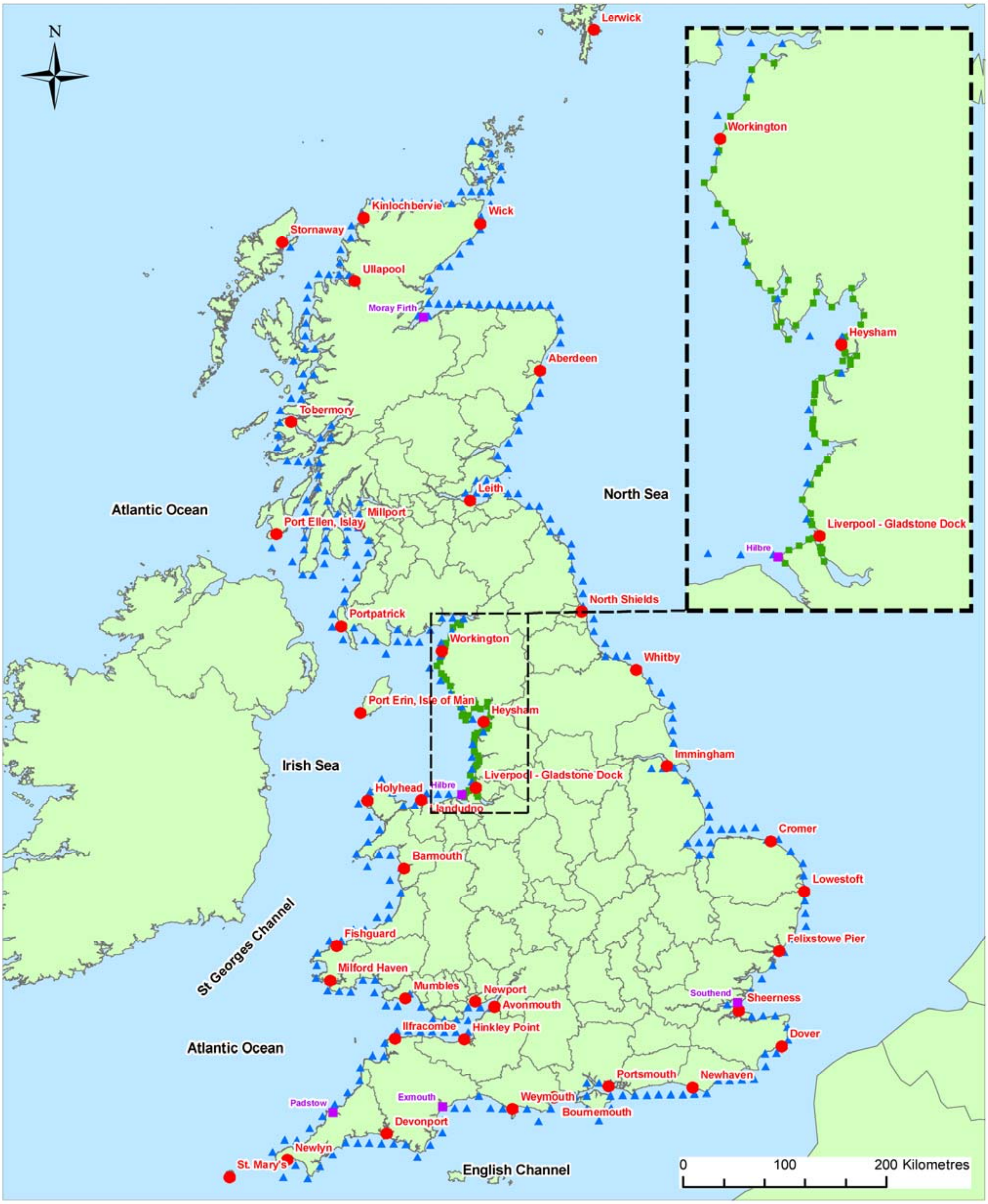
Date:
2010

Scale @A4:
1:5,000,000

Figure:
2.1

Source / Copyright

I:\9S7299\Technical_Data\F12_GIS\Projects\Report_Figures\Extreme_Sea_Levels



Key:

■ Supplementary Gauges

● Class A Sites

▲ CSX3 Model Points

■ North East Irish Sea Model Points

Source / Copyright

I:\9S7299\Technical_Data\F12_GIS\Projects\Report_Figures\Extreme_Sea_Levels

Title: Model Output Points	Figure: 2.2
Project: SC060064: Development and Dissemination of Coastal and Estuary Extremes	
Client: Environment Agency	
Date: 2010	Scale @A4: 1:5,000,000

Key:

● Class A Sites

■ Supplementary Gauges

Source / Copyright

I:\9S7299\Technical_Data\F12_GIS\Projects\Report_Figures\Extreme_Sea_Levels

Title:
Primary Tide Gauge Sites

Project:
SC060064: Development and Dissemination of Coastal and Estuary Extremes

Client:
Environment Agency

Date:
2010

Scale @A4:
1:5,000,000

Figure:
3.1

defra
Department for Environment Food and Rural Affairs

Environment Agency

ROYAL HASKONING

SEPA
Scottish Environment Protection Agency

List of abbreviations

Defra	Department for Environment, Food and Rural Affairs
POL	Proudman Oceanographic Laboratory
SEPA	Scottish Environment Protection Agency
GIS	Geographic Information Systems
POLTIPS 3	Proudman Oceanographic Laboratory Tidal Prediction Software 3
BODC	British Oceanographic Data Centre
SSJPM	Skew Surge Joint Probability Method
CSX3	POL Continental Shelf Tide-Surge Model
NEIS	JBA North East Irish Sea model
ERA 40	European Centre for Medium-Range Weather Forecasts Re-analyses of meteorological data (1957 – 2001) giving representative time series historic conditions in a grid format
GEBCO	Generalised Bathymetry Chart of the Oceans
IHO	International Hydrographic Organisation
IOC	International Oceanographic Commission
UNESCO	United Nations Education Scientific and Cultural Organisation
LiDAR	Light Detection And Ranging
GPD	Generalised Pareto Distribution
NTSLF	National Tidal and Sea Level Facility
ABP	Associated British Ports
EA	Environment Agency
MAFF	Ministry of Agriculture Fisheries and Food

Glossary

Annual Exceedance Probability:	The probability (likelihood) of being exceeded in any given year.
Astronomical tide:	The periodic rise and fall of a body of water resulting from gravitational interactions between Sun, Moon, and Earth.
Bathymetry:	The study of underwater depth
Class A tide gauge:	Tide gauge site operated by BODC on behalf of NTSLF
Primary site:	Sites at which tide gauge data has been analysed using SSJPM statistical analysis
Secondary site:	Gauge data used to validate and correct the numerical model results
Datum:	A reference point from which measurements are made
Chart Datum:	The level of water that charted depths are measured from, usually the predicted lowest astronomical tide
Ordnance Datum:	Vertical datum used by an ordnance survey. The height above sea level based on a known datum point.
Extreme Sea Levels:	The highest elevation reached by the sea as recorded by a water level gauge during a given period
Estuary	Partially enclosed body of water where saline water from the sea meets fresh water from terrestrial sources
Intertidal	The portion of the shoreline that is submerged during an average high tide and exposed at an average low tide
LiDAR:	Light Detection And Ranging (LiDAR) is an optical remote sensing technology that measures properties of scattered light to find range of a distant target
Lunar declination:	Precession of the lunar orbit, while this orbit maintains a 5° tilt relative to the ecliptic
Lunar nodal cycle:	The 18.6 year cycle caused by the precession of the plane of the lunar orbit
Mean High Water Spring Tide	The average of high water heights occurring at the time of spring tides

Semi-diurnal tide	Tide which has a cycle of approximately half of one tidal day, therefore two high and low tides per day
Skew surge:	Difference in level between peak observed tide and peak predicted tide
Sonar:	A measuring instrument that sends out an acoustic pulse in water and measures distances in terms of time for the pulse to return
Storm surge:	A rise above normal water level on the open coast due to the action of wind stress and atmospheric pressure upon the water surface
Tidal constituents:	One of the harmonic elements in a mathematical expression for the tide-producing force and in corresponding formulas for the tide or tidal current. Each constituent represents a periodic change or variation in the relative positions of the Earth, Moon, and Sun
Tidal Flats:	Deposited mud or sand areas periodically covered by tidal waters
Wave Set-up:	The superelevation of mean water level at the coast as caused by breaking incident waves
Tidal constituents:	One of the harmonic elements in a mathematical expression for the tide-producing force and in corresponding formulas for the tide or tidal current. Each constituent represents a periodic change or variation in the relative positions of the Earth, Moon, and Sun

Appendix 1 Tide Level Data Available to the Analysis

A1.1 Introduction

The listings given on the following pages present the source, range and quality for the tide gauge records used towards the present derivation of extreme tide levels.

- Records from the UK National Network of Tide Gauges (often referred to as the 'Class A' tide gauge network, now used to describe these gauges in this report) run by the Tide Gauge Inspectorate at the National Tidal and Sea Level Facility, part of the Proudman Oceanographic Laboratory;
- Gauge data supplied specifically for this project by the Environment Agency;
- Gauge data supplied specifically for this project by the Scottish Environment Protection Agency;
- Third Party Tide Gauge Data, kindly supplied by the following organisations:
    - Associated British Ports
    - British Oceanographic Data Centre, part of the Proudman Oceanographic Laboratory.
    - Falmouth Harbour Commissioners
    - Port of London Authority
    - UK Dredging;
- Mean High Water Spring tide levels from Admiralty Tide Tables; and
- Mean High Water Spring tide levels from POLTIPS3.

Table A1.1 contains details of all Class A tide gauge data obtained for this project. **Table A1.2** contains details of all Environment Agency and Third Party tide gauge data obtained for this project.

A1.2 British Oceanographic Data Centre Review

Tide gauge data supplied by the Environment Agency, Scottish Environmental Protection Agency, Associated British Ports, Falmouth Harbour Commissioners, Falmouth Harbour Commissioners and UK Dredging were quality checked by the British Oceanographic Data Centre. **Figure A1.1** shows the procedures undertaken by BODC to quality check the tide gauge data.

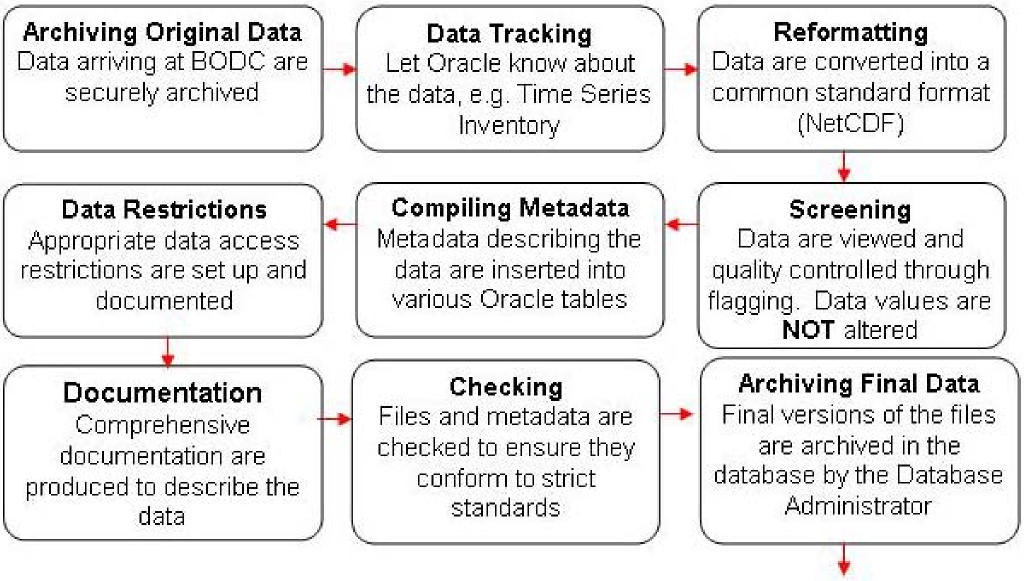


Figure A1.1 – BODC Data Processing Steps

The quality checked data and details on the Environment Agency operated gauges can be accessed by contacting the Environment Agency. For third party gauge data, please contact the gauge owners, as given in **Table A1.2**.

A1.3 Data Review

We also undertook a separate review of gauge data by plotting each year’s data graphically and then visually inspecting it for flaws. Common flaws in the data include:

- Missing Data
- ‘Spikes’ where the gauge appears to be recoding anomalously high levels, significantly above the usual peak levels.
- Datum shifts, in these cases the data suddenly moves from one level to another.
- Datum drift, where the datum appears to progressively decrease or increase in level over the course of the year.
- Levels that are influenced by fluvial discharges resulting in higher recorded levels that would be produced by tidal influences alone.

This assessment of data quality is summarised in **Table A1.3**. For each year of gauge data one of the following four quality classes have been assigned. It should be noted that this is a subjective process and the division between the classes are naturally a grey area.

- Good: Data is fully or mostly complete, with no flaws affecting the higher levels around spring tides in the winter months which will be used in the analysis.
- Reasonable: Some flaws in the data requiring filtering of the data in the detailed analysis to give reliable peak tide level values.
- Poor: Numerous flaws and/or incomplete record in the winter months that will prohibit the use of the data from determining reliable peak tide levels.
- No Data: These are years where no data has been obtained for the gauge.

Table A1.1 Class A Tide Gauge Data

Site	Nominal Period of Record	Source
Newlyn	1915-2009	NTSLF
St Mary's (Isles of Scilly)	1976 1994-2009	NTSLF
Ilfracombe	1968-1971 1977-2000 2002-2009	NTSLF
Hinkley Point	1990-2009	NTSLF
Avonmouth	1961/1962 1973-1976 1980-1984 1986-2008	NTSLF
Newport	1993-2009	NTSLF
Mumbles	1988-1993 1997-2009	NTSLF
Milford Haven	1953-1954 1961-1962 1964-1965 1967-2009	NTSLF
Fishguard	1963-2009	NTSLF
Barmouth	1991-2008	NTSLF
Llandudno	1971 1994-2009	NTSLF
Holyhead	1964-1973 1977-1985 1987-1991 1995-2009	NTSLF
Gladstone Dock (Liverpool)	1991-2009	NTSLF
Port Erin (Isle of Man)	1992-1995 1998-2009	NTSLF
Heysham	1964-1969 1971-2009	NTSLF
Workington	1992-2009	NTSLF
Portpatrick	1968-2009	NTSLF
Millport	1978 1981-1983 1985-2009	NTSLF

Site	Nominal Period of Record	Source
Port Ellen (Isle of Islay)	1979-1980 1991-2009	NTSLF
Tobermory (Mull)	1990-2009	NTSLF
Ullapool	1966-1968 1970-1972 1974-2009	NTSLF
Stornoway (Hebrides)	1976 1978-1981 1983 1985-2009	NTSLF
Kinlochbervie	1991-2001 2003-2009	NTSLF
Lerwick (Shetland Isles)	1959-2009	NTSLF
Wick	1965-1970 1972-2009	NTSLF
Aberdeen	1930-1936 1946-1958 1960-1962 1964-1975 1980-2008	NTSLF
Leith	1981 1989-2009	NTSLF
North Shields	1946-1947 1949-1956 1961-1962 1964-1975 1978-2009	NTSLF
Whitby	1980-2009	NTSLF
Immingham	1953 1956-1958 1963-2009	NTSLF
Cromer	1973/1974 1976 1989-2008	NTSLF
Lowestoft	1964-2009	NTSLF
Felixstowe	1982, 1984 1986-2009	NTSLF

Site	Nominal Period of Record	Source
Sheerness	1952 1958 1965-1975 1980-2009	NTSLF
Dover	1924, 1926, 1928, 1930 1934-1936 1938 1958-2009	NTSLF
Newhaven	1982-1987 1991-2009	NTSLF
Portsmouth	1991-2009	NTSLF
Bournemouth	1996-2008 Amax series (1974-1990)	NTSLF Environment Agency (South West Region)
Weymouth	1991-2009	NTSLF
Devonport	1987 1991-2008 Amax series (1920-1936) Amax series ((1953-1990)	NTSLF Environment Agency (South West Region)

Table A1.2 Environment Agency and Third Party Tide Gauge Data

Note – This table refers to time-series data, unless stated otherwise

Site	Nominal Period of Record	Source
Padstow	1998-2007	EA, South West
Minehead	2000-2008	EA, South West
Uphill	1992-1994 1998-2000 2002/2003 2006-2008	EA South West
Cardiff	2004-2007	UK Dredging, ABP
Swansea	2004-2007	UK Dredging, ABP
Llanelli	2004-2008	EA, Wales
Aberystwyth	2004-2008	EA, Wales
Porthmadog	1993-2008	EA, Wales
Hilbre Island	1964-1968 1974/1975 1977-1981 1990-2003	BODC
Fleetwood	1995-2008	EA, North West
Lancaster Quay	1993-2008	EA, North West
Winster Sluice	1993-2008	EA, North West
Canal Foot	1994-2008	EA, North West
Ramsden Dock, Barrow	1992-1996 1998-2008	ABP
Girvan	1997-2002 2007/2008	SEPA
Tarbert	1995-2008	SEPA
Corpach	1992-2008	SEPA
Orkney Islands	1993-2008	SEPA
Moray Firth	1994-2004	NTSLF
Buckie	2001-2008	SEPA
Newport-on-Tay	1995-2008	SEPA
Berwick	2005-2008	EA, North East

Site	Nominal Period of Record	Source
Tees Dock	1992-2008	EA, North East
Bridlington	1997-2008	EA, North East
Burgh Sluice	1990-2008	EA, Anglian
West Lynn	1995-2008	EA, Anglian
Wells	1992-2008	EA, Anglian
Great Yarmouth	1992-2008	EA, Anglian
Southwold	1992-1995 1997-2008	EA, Anglian
Clacton	2001-2008	EA, Anglian
Southend	1929-1983 1994-2001	POL, funded by MAFF EA, Port of London Authority
Margate	1994-2007	Port of London Authority
Rye	1992-2008	EA, Southern
Pevensey	1992-2008	EA, Southern
Littlehampton	1992-2008	EA, Southern
Woolston Tide	1993-1999	EA, Southern
Calshot	1990-2008	ABP
Cowes	1998/1999 2004-2008	EA, Southern
Lymington	1992-1999 2003-2008	EA, Southern
Exmouth	2000-2008 Amax series (1973-1997)	EA, South West
Teignmouth	2005-2008	EA, South West
Falmouth	2002-2008	Falmouth Harbour Commissioners

Table A1.3 - Summary of Data Quality from Secondary Sources

Note: This table only relates to time-series data

Key: (quality of data)
🟩 Good
🟨 Reasonable (Minor gaps and errors (eg high water spikes))
🟥 Poor (Large gaps and /or many erors and/or uncertain datum)
⬜ No Data (No record or data in supplied record)

Site	Data Source	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Padstow	EA, South West	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟥
Minehead	EA, South West	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟩	🟥	🟩	🟩	🟩	🟩	🟩
Uphill	EA, South West	⬜	⬜	🟥	🟥	🟥	⬜	⬜	⬜	🟥	🟥	🟥	⬜	🟥	🟥	⬜	⬜	🟥	🟩	🟩
Cardiff	UK Dredging, ABP	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟨	🟨	🟨	🟨	⬜
Swansea	UK Dredging, ABP	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟨	🟨	🟨	⬜
Llanelli	EA, Wales	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟩	🟩	🟥
Aberystwyth	EA, Wales	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟨	🟥	🟩
Porthmadog	EA, Wales	⬜	⬜	⬜	🟥	🟩	🟩	🟨	🟩	🟩	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟥
Hilbre Island	BODC	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟥	🟩	🟩	🟩	🟨	⬜	⬜	⬜	⬜	⬜
Fleetwood	EA, North West	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟩	🟨	🟩	🟥	🟩	🟩	🟩	🟨	🟥	🟩	🟩	🟨
Lancaster Quay	EA, North West	⬜	⬜	⬜	🟥	🟥	🟨	🟩	🟩	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Winster Sluice	EA, North West	⬜	⬜	⬜	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟨	🟩	🟩	🟩	🟥	🟥
Canal Foot	EA, North West	⬜	⬜	⬜	⬜	🟥	🟩	🟥	🟥	🟩	🟥	🟩	🟥	🟥	🟩	🟨	🟥	🟨	🟨	🟥
Ramsden Dock	ABP	⬜	⬜	🟥	🟥	🟨	🟥	🟥	⬜	🟨	🟨	🟩	🟥	🟥	🟥	🟨	🟥	🟩	🟥	🟨
Girvan	SEPA	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟥	🟩	🟩	🟥	⬜	⬜	⬜	⬜	🟥	🟥
Tarbert	SEPA	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟩
Corpach	SEPA	⬜	⬜	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Buckie	SEPA	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨
Newport	SEPA	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟩	🟥	🟩	🟩	🟨	🟩	🟥	🟨	🟨	🟩	🟨	🟥
Berwick	EA, North East	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟩	🟥
Tees Dock	EA, North East	⬜	⬜	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Bridlington	EA, North East	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟥	🟥	🟨	🟨	🟨	🟥	🟩	🟩	🟩	🟩
Burgh Sluice	EA, Anglian	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟥
West Lynn	EA, Anglian	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟩	🟨	🟨	🟩	🟨	🟥	🟥	🟨	🟩	🟩	🟨	🟥
Wells	EA, Anglian	⬜	⬜	🟥	🟩	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟥
Great Yarmouth	EA, Anglian	⬜	⬜	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟥
Southwold	EA, Anglian	⬜	⬜	🟥	🟥	🟥	🟥	⬜	🟥	🟨	🟨	🟨	🟥	🟨	🟨	🟥	🟨	🟨	🟨	🟨
Clacton	EA, Anglian	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟩	🟥	🟩	🟩	🟥	🟥
Southend	Port of London Authority	⬜	⬜	⬜	⬜	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟨	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Margate	Port of London Authority	⬜	⬜	⬜	⬜	🟥	🟨	🟨	🟥	🟨	⬜	🟩	🟨	🟩	🟩	🟩	🟨	🟨	🟩	⬜
Rye	EA, Southern	⬜	⬜	🟥	🟥	🟨	🟩	🟩	🟨	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Pevensey	EA, Southern	⬜	⬜	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟥	🟨	🟥	🟨	🟥
Littlehampton	EA, Southern	⬜	⬜	🟥	🟥	🟨	🟩	🟨	🟨	🟩	🟥	🟩	🟩	🟥	⬜	🟥	🟩	🟩	🟩	🟥
Woolston Tide	EA, Southern	⬜	⬜	⬜	🟥	🟨	🟨	🟥	🟩	🟩	🟥	⬜	⬜	⬜	⬜	🟨	🟥	🟨	🟨	🟥
Calshot	ABP	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟥	🟨	🟩	🟩	🟩	🟩	🟩
Cowes	EA, Southern	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	⬜	⬜	⬜	⬜	🟩	🟩	🟩	🟨	🟥
Lymington	EA, Southern	⬜	⬜	🟥	🟥	🟨	🟥	🟥	🟩	🟩	🟥	⬜	⬜	⬜	🟥	🟩	🟨	🟥	🟩	🟩
Exmouth	EA, South West	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟩	🟥	🟩	🟨	🟩	🟨	🟨	🟥
Teignmouth	EA, South West	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟨	🟩	🟥
Falmouth	Falmouth Harbour Commissioners	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Site	Data Source	1964	1965	1966	1967	1968	1974	1975	1977	1978	1979	1980	1981
Hilbre Island	BODC	🟨	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩

Appendix 2 Schedule of Datums and Other Values

Table A2.1 - Schedule of Datums and High Levels at Class A Sites

Notes:
1. Information is from the Admiralty Tide Tables
2. Data referenced to local datum
3. Highest level is taken from a review of the digital gauge record. Levels corrected to 2008. The review aimed to identify, and filter out, spurious high water levels. No value is given where there is an insubstantial record from the site.
4. This level has been taken from Amax series provided by the Environment Agency.

Site Name	Tide Level Gauge	Grid Reference	Gauge Datum	Chart Datum Adjustment (metres relative to OD) (note 1)	Highest Level in Records (note 3)	
					mOD	Date
Newlyn	NTSLF	SW 4676 2856	CD	-3.05	3.39	29 January 1948
St. Mary's	NTSLF	SV 9027 1097	CD	-2.91 (note 2)	3.55 (note 2)	30 March 2006
Ilfracombe	NTSLF	SS 5264 4786	CD	-4.80	5.71	07 April 1985
Hinkley	NTSLF	ST 2086 4684	CD	-5.90	7.38	10 February 1997
Avonmouth	NTSLF	ST 5047 7934	CD	-6.50	8.98	13 December 1981
Newport	NTSLF	ST 3163 8392	CD	-5.81	7.85	10 February 1997
Mumbles	NTSLF	SS 6323 8756	CD	-5.00	5.66	29 August 1992
Milford Haven	NTSLF	SM 8926 0526	CD	-3.71	4.49	23 September 1953
Fishguard	NTSLF	SM 9538 3923	CD	-2.44	3.37	10 February 1997
Barmouth	NTSLF	SH 6197 1548	CD	-2.44	3.94	10 February 1997
Holyhead	NTSLF	SH 2553 8287	CD	-3.05	3.82	01 February 2002
Llandudno	NTSLF	SH 7855 8319	CD	-3.85	5.12	10 February 1997
Liverpool - Gladstone Dock	NTSLF	SJ 3248 9525	CD	-4.93	5.91	10 February 1997
Port Erin, Isle of Man	NTSLF	SC 1904 6902	CD	-2.81 (note 2)	3.72 (note 2)	01 February 2002
Heysham	NTSLF	SD 3982 5993	CD	-4.90	6.71	01 February 1983
Workington	NTSLF	NX 9894 2954	CD	-4.20	5.78	10 February 1997
Portpatrick	NTSLF	NW 9976 5421	CD	-1.80	3.40	05 January 1991
Millport	NTSLF	NS 1772 5452	CD	-1.62	3.48	05 January 1991
Port Ellen, Islay	NTSLF	NR 3634 4506	CD	-0.19	1.79	26 December 1998
Tobermory	NTSLF	NM 5080 5529	CD	-2.39	3.68	11 January 2005
Ullapool	NTSLF	NH 1292 9391	CD	-2.75	3.70	12 January 2005
Stornoway	NTSLF	NB 4228 3265	CD	-2.71 (note 2)	3.21 (note 2)	10 February 1997
Kinlochbervie	NTSLF	NC 2213 5609	CD	-2.50	3.78	12 January 2005
Lerwick	NTSLF	HU 4783 4137	CD	-1.22 (note 2)	1.85 (note 2)	11 January 1993
Wick	NTSLF	ND 3667 5081	CD	-1.71	2.80	12 January 2005
Aberdeen	NTSLF	NJ 9524 0591	CD	-2.25	3.06	12 January 2005
Leith	NTSLF	NT 2638 7806	CD	-2.90	3.66	09 February 1997
North Shields	NTSLF	NZ 3593 6824	CD	-2.60	3.67	31 January 1953
Whitby	NTSLF	NZ 8985 1133	CD	-3.00	3.66	01 February 1983
Immingham	NTSLF	TA 2000 1647	CD	-3.90	4.83	01 February 1983
Cromer	NTSLF	TG 2198 4253	CD	-2.75	3.53	21 February 1993
Lowestoft	NTSLF	TM 5483 9273	CD	-1.50	2.79	29 September 1969
Felixstowe	NTSLF	TM 3017 3398	CD	-1.95	3.02	21 February 1993
Sheerness	NTSLF	TQ 9074 7542	CD	-2.90	4.11	10 December 1965
Dover	NTSLF	TR 3264 4026	CD	-3.67	4.41	02 February 1983
Newhaven	NTSLF	TQ 4511 0004	CD	-3.05	4.22	02 February 1983
Portsmouth	NTSLF	SU 6269 0071	CD	-2.73	2.80	23 December 1995
Bournemouth	NTSLF	SZ 0893 9053	CD	-1.40	1.69	10 March 2008
Weymouth	NTSLF	SY 6840 7885	CD	-0.93	2.11	10 March 2008
Devonport	NTSLF	SX 4469 5434	CD	-3.22	3.31 (note 4)	1985 (note 4)

Table A2.2 - Schedule of Datums and High Levels at Validation and Supplementary Gauge Sites

Notes:
1. Information is from the Admiralty Tide Tables
2. Data referenced to local datum
3. Highest level is taken from a review of the digital gauge record. Levels corrected to 2008. The review aimed to identify, and filter out, spurious high water levels. No value is given where there is an insubstantial record from the site.
4. Supplementary gauge sites used for statistical analysis

Site Name	Tide Level Gauge	Grid Reference	Gauge Datum	Chart Datum Adjustment (metres relative to OD) (note 1)	Highest Level in Records (note 3)	
					mOD	Date
Padstow (note 4)	EA, South West	SW 91995 75470	CD	-3.80	4.70	30-Mar-08
Minehead	EA, South West	SS 97134 47116	OD	-5.40	6.92	30-Mar-06
Uphill	EA, South West	ST 31444 58496	OD		7.61	08-Oct-06
Cardiff	UK Dredging, ABP	ST 19373 73988	Local	-6.30 (note 2)	7.87 (note 2)	30-Mar-06
Swansea	UK Dredging, ABP	SS 66877 91884	Local	-5.00 (note 2)	5.88 (note 2)	30-Mar-06
Llanelli	EA, Wales	SS 50384 98626	OD	-3.66	5.47	30-Mar-06
Aberystwyth	EA, Wales	SN 58190 81327	OD	-2.44	4.02	10-Mar-08
Porthmadog	EA, Wales	SH 57267 38577	CD	-2.44	3.83	10-Feb-97
Hilbre Island (note 4)	BODC	SJ 1844 8809	CD	-4.93	5.73	14-Apr-64
Fleetwood	EA, North West	SD 3412 4829	OD	-4.90	6.27	01-Feb-02
Lancaster Quay	EA, North West	SD 4628 6208	CD	-0.01	6.81	01-Feb-02
Winster Sluice	EA, North West	SD 43233 79044	OD	Not known	6.49	10-Feb-97
Canal Foot	EA, North West	SD 3136 7768	OD	-4.70	6.87	10-Feb-97
Ramsden Dock, Barrow	ABP	SD21626 67789	CD	-4.75	6.29	01-Feb-02
Girvan	SEPA	NX 18302 98157	CD	-1.40	3.01	25-Dec-99
Tarbert	SEPA	NR 86574 68729	CD	-1.62	3.07	01-Feb-02
Corpach	SEPA	NN 09561 76611	CD	-1.98	5.65	11-Jan-05
Buckie	SEPA	NJ 43200 66060	CD	-2.10	2.95	20-Jun-03
Moray Firth	NTSLF	NH 8043 5834	CD	-2.10	3.12	04-Dec-94
Newport	SEPA	NO 41790 27649	OD	-2.90 (note 2)	3.77 (note 2)	12-Jan-05
Berwick	EA, North East	NT 99779 52641	OD	-2.50	3.28	30-Mar-06
Tees Dock	EA, North East	NZ 54328 23472	OD	-2.85	3.77	12-Jan-05
Bridlington	EA, North East	TA 18651 66420	OD	-3.35	3.75	12-Jan-05
Burgh Sluice	EA, Anglian	TF 5519 5862	OD	Not known	4.59	09-Feb-97
West Lynn	EA, Anglian	TF 6135 2025	OD	-3.03	5.26	19-Sep-01
Wells	EA, Anglian	TF 9158 4393	OD	-0.75	4.27	01-Jan-95
Great Yarmouth	EA, Anglian	TG 5342 0369	OD	-1.59	2.67	21-Feb-93
Southwold	EA, Anglian	TM 5014 7500	OD	-1.30	2.59	21-Feb-93

Site Name	Tide Level Gauge	Grid Reference	Gauge Datum	Chart Datum Adjustment (metres relative to OD) (note 1)	Highest Level in Records (note 3)	
Clacton	EA, Anglian	TM 17845 14287	OD	-2.29	3.13	16-Dec-05
Southend (note 4)	Port of London Authority/EA Southern/POL	TQ89056 83080	CD	-2.90	4.68	05-Feb-53
Margate	Port of London Authority	TR 35128 71152	CD	-2.50	3.42	28-Jan-94
Rye	EA, Southern	TQ 94371 19104	OD	-1.55	4.93	01-Jan-95
Littlehampton	EA, Southern	TQ 0272 0176	OD	-2.74	3.71	24-Dec-95
Woolston Tide	EA, Southern	SU 4324 1024	OD	-2.74	2.88	10-Mar-08
Calshot	ABP	SU 4881 0258	CD	-2.74	2.70	23-Dec-95
Cowes	EA, Southern	SZ 4967 9622	OD	-2.59	2.64	10-Mar-08
Lymington	EA, Southern	SZ 3275 9605	OD	-1.98	2.17	10-Mar-08
Exmouth (note 4)	EA, South West	SX 99350 80668	CD	-1.83	2.97	10-Feb-74
Teignmouth	EA, South West	SX 93880 72690	CD	-2.65	2.89	10-Mar-08
Falmouth	Falmouth Harbour Commissioners	SW 81898 32606	Local	-2.65 (note 2)	3.23 (note 2)	27-Oct-04

Appendix 3 Derivation of Sea Levels

A3.1 Introduction

This appendix describes in detail the derivation of sea levels, and application of the Skew Surge Joint Probability Method (SSJPM), which is the method used to derive the extreme sea levels for the Environment Agency/Defra Research and Development project SC060064: Coastal and Estuary Extremes.

The general approach for derivation of the extreme sea levels is outlined in **Section 3** of the main report. This Appendix gives detail of the analyses made, both as a background to the results and as a reference for any further update of the levels at some time in the future.

A listing of gauge data and flood event information used for the analysis is given here in **Appendix 1**. Also used to aid the analysis were findings from the coastal modelling (described in **Appendix 4**).

This technique uses real data at the National Tidal and Sea Level 'Class A' sites and nominated supplementary sites to generate a marginal (individual) probability distribution for predicted high waters and surge caused by meteorological effects, defined by the skew surge parameter. The method forms the probability distribution of total sea level from the joint probability distribution of predicted high tide and skew surge. The probabilities of extreme total sea levels are then expressed as return periods. This provides the return periods for the Class A sites and nominated supplementary, jointly termed the primary sites.

A3.2 The Coastline

A3.2.1 Chainage System

An arbitrary chainage system was set up along a line broadly following the coast. Chainage zero was taken as Newlyn, chosen as it has the longest data record and is one of the primary gauges where statistical analysis is undertaken. The line then extends clockwise around the coast of England, Wales and Scotland. The purpose of the chainage system was to facilitate interpolation of predicted tide levels for intermediate sites between the primary analysis sites.

A3.2.2 Mean High Water Springs Tides

MHWS tide levels were calculated for coastal locations. The MHWS levels were taken from the POLTIPS software.

The MHWS values were plotted at their respective chainage, these points then being used to draw a coastal MHWS tide level trend line (**Figure A3.13 to A3.17**). The trend line is drawn to give a sensible smooth progression of MHWS tide level around the coast.

A3.3 Data

Time series data was obtained from the UK Tide Gauge Network, operated and maintained by the National Tidal and Sea Level Facility (NTSLF), part of Proudman

Oceanographic Laboratory (POL). Two channels provide data at UK Tide Gauge Network sites. This enables a second channel to be used in the case of the primary channel ceasing operation for a particular reason. The data used for this project was the ‘best available channel’ for each tide gauge, ensuring maximum data coverage.

The gauges are regularly checked by the NTSLF and any missing or suspect (spikes, datum shifts, spurious readings, etc.) records are removed. We have plotted the data for all 40 sites as a sensibility check and no datum shifts or spikes were apparent. For the purposes of the skew surge methodology data gaps are acceptable, as the method is applied to all available data. Data was at 15 minute intervals (averaged instantaneous values over the 15 minutes) for recent data with older data at 1 hour intervals. Datums were checked and corrected to Ordnance Datum using information from the National Tidal and Sea Level Facility.

At each gauge site, the time series of total sea level was detrended using a sea level rise rate of 2mm per year. The rate used is the net combination of land movement and changes in water level. Analysis by the NTSLF shows this historic rate to be common around the UK coast. The base year to which the mean of the total sea level data was set is 2008, i.e. the most recent complete annual coverage of tide gauge data used in the analysis.

A3.4 Skew Surge Joint Probability

A3.4.1 Marginal Analysis of Skew Surge and Predicted Tides

The peak high water levels for each observed tidal event were identified and the nearest predicted high tide selected. The difference between the peak of the observed total sea level and nearest peak predicted level is the **skew surge**, as shown in **Figure A3.1**.

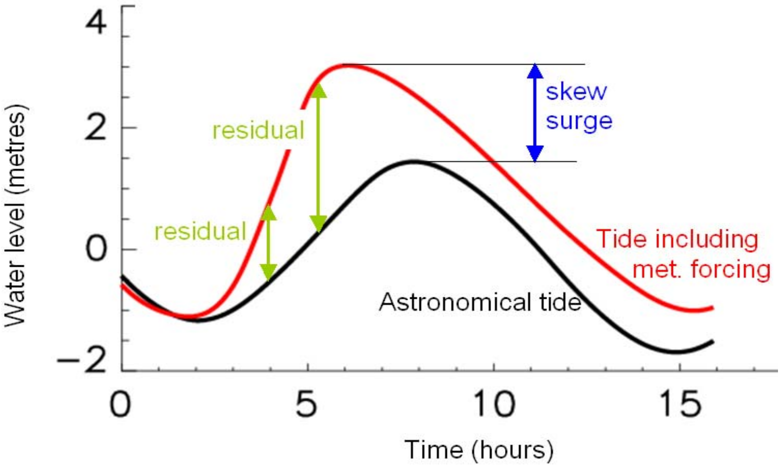


Figure A3.1- Illustration of the skew surge. It is the difference between the predicted astronomical high tide (black line) and the nearest observed high water in the observational record (red line).

This process was repeated for all high water events for each year of data. As the semi-diurnal tidal period is 12.42 hours, this leads to approximately 705 values of skew surge with corresponding peak predicted tide each year.

A statistical model requires the following: first, a random variable X (say skew surge value) which represents a quantity whose outcome is uncertain and has a set of possible outcomes, denoted Ω. This is the sample space. Second, a probability distribution, which assigns probabilities to events associated with X. Most of the random variables to which extreme value techniques are applied are continuous random variables. Therefore they have a sample space, Ω, that is continuous. Because of the continuity it is not possible to assign probabilities to all possible values of the random variable in a meaningful way; there are too many possible values on a continuous scale. Instead, probability distributions can be specified by their probability distribution function, defined as:

$$F(x) = \Pr\{X \leq x\},$$

for each x in Ω. For the usual axioms of probability to be satisfied, F must be a non-decreasing function of x, such that $F(x_-) = 0$ and $F(x_+) = 1$, where x_- and x_+ are the lower and upper limits of Ω, respectively (Coles, 2001).

To generate the probability distributions for skew surge and predicted high tide, histograms of the frequency of the data were first calculated. A histogram of skew surge values for an example gauge location is shown in **Figure A3.2a**. The probability density function, shown in **Figure A3.2b**, is derived from the histogram of values by dividing by the total number of observations.

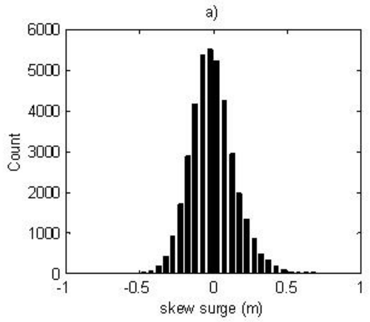


Figure A3.2: (a) Histogram of skew surge values

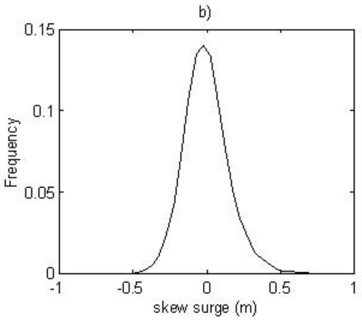


Figure A3.2: (b) Probability Density Function of skew surge values

Storm surges forced by variations in atmospheric pressure and wind represent a stochastic process. By their nature, observations of extreme values of such a process. Consequently, the tails of the probability density function for skew surge can be poorly resolved. **Figure A3.3a** shows the number of large skew surges for specific levels observed at an example gauge site. Although the trend in the number is generally decreasing with increasing level, the lack of observations means this trend can be inconsistent. This behaviour is transferred to the probability density function, which is derived from the histogram, shown in **Figure A3.3b**. In reality, the probability density function should be a monotonically decreasing function for increasingly extreme skew surge levels. Therefore, a statistical model was fit to the upper tail in order to simulate this behaviour.

The statistical model used is the Generalized Pareto Distribution (GPD). The GPD was fit to the extreme value skew surges above a specific threshold level. The threshold used was the 97.5 percentile of the skew surge values. The parameters of shape and scale define the GPD and were determined from the extreme value data using the method of **maximum likelihood**. A recommended and widely-used method for fitting extreme value distributions, the maximum likelihood method seeks to find values of the distribution parameters that maximize the likelihood function. The procedure follows from the notion that the likelihood is a measure of the degree to which the data support particular values of the parameters. An interpretation would be that the maximum-likelihood estimators are the most probable values for the parameters, given the observed data.

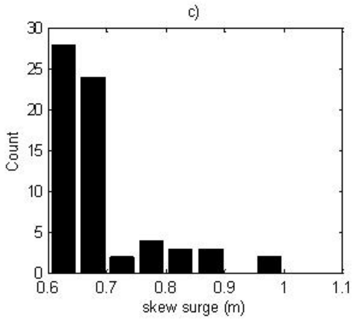


Figure A3.3: (a) Histogram of skew surge values: highest levels shown

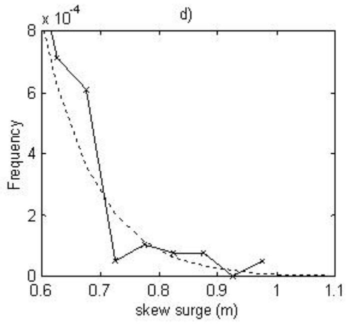


Figure A3.3: (b) Probability density function of skew surge values: highest levels shown. The dashed line shows the fitted Generalised Pareto Distribution.

For small variations of the threshold value, the probability distribution function can exhibit inconsistent variation, as can be seen for the extreme skew surge values (Figure **A3.3b**). As this is the location to which the GPD is fit, this variation can have a significant effect on the tail fitting. **Figure A3.4** shows an example skew surge distribution with the GPD fit to three different thresholds. This example, though exaggerated for visual clarity, reveals the discrepancies that can arise. In order to prevent small variations of the threshold value having such an impact on the GPD fit, the skew surge distribution was smoothed using the Kernel Density Estimation technique. This technique associates a kernel function to each data point of the skew surge density function. The smoothed skew surge density function is then the sum of all the kernel functions. The kernel functions depend on a parameter, termed the bandwidth, which significantly affects the roughness or smoothness of the kernel function that is ultimately generated. Sensitivity tests showed that, for slight variations from recommended values for the bandwidth, there was negligible change to the GPD fit.

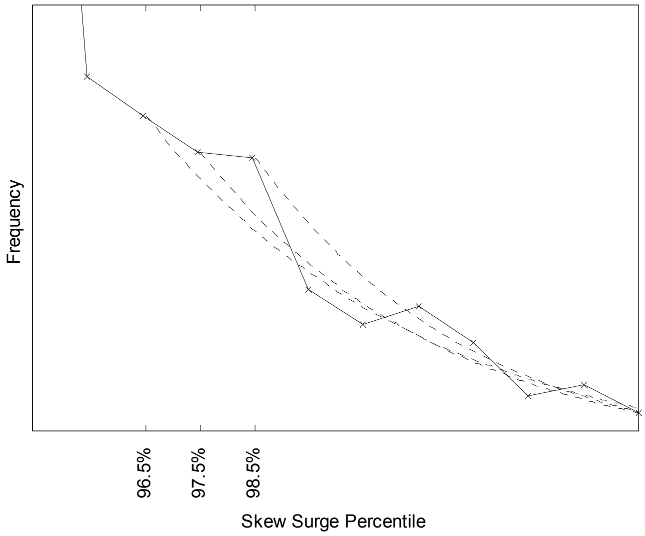


Figure A3.4: Unsmoothed probability density function of skew surge: changes to location of GPD fit

For each gauge site, the lunar nodal cycle of high tides was derived from harmonic constituents. This cycle has an approximate period of 18.6 years. It is caused by the precession of the plane of the lunar orbit, while this orbit maintains a 5° tilt relative to the ecliptic. The maximum lunar monthly declination during this cycle north and south of the equator varies between 18°18' and 28°36'. **Table A3.1** shows the years at which the maximum lunar declination and the minimum lunar declination occur.

Table A3.1: Maximum and minimum lunar declinations (www.pol.ac.uk/ntslf)

Minimum lunar declination	1978	1997	2015	
Maximum lunar declination	1969	1987	2006	2025

Modulations by this variation in lunar declination can increase (decrease) the range of the tide by 3.7% when the declination amplitudes are smallest (greatest).

As opposed to storm surge levels, peak tide levels due solely to astronomical tidal forcing are deterministic. The distribution of peak tide levels therefore exhibit well-resolved tails and there is no requirement to fit a GPD for increased resolution. An example of the distribution of peak tide levels during the lunar nodal cycle is given in **Figure A3.5**.

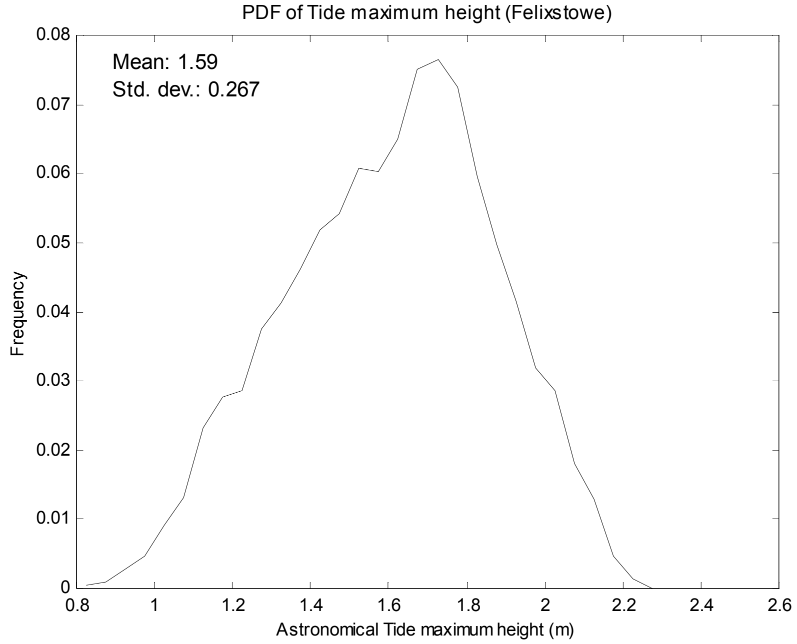


Figure A3.5: An example distribution of peak tide levels

A3.4.2 Joint Probability Analysis

Joint probability analysis aims to form a probability distribution of all possible total sea levels from the skew surge distribution (with GPD tail fit) and peak tide levels from the nodal cycle. Specifically, 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. For a total water level, x, the probability function is,

$$F_{TSL}(x) = [\ \pi_{t=1..T}\ F_{SS}(x-X_t)\ ]^{1/T}$$

where X is the peak tide level, T is the total number of peak tide levels, and F_{SS} is the probability function of skew surge, expressed for a level, z, as,

$$F_{SS}(z) = (\#\{Y_1,\ldots,Y_T\} < z) \div T \quad \text{if } z < u$$

$$F_{SS}(z) = 1 - [(\#\{Y_1,\ldots,Y_T\} < z) \div T]*[1 + \zeta(z - u) \div \sigma]^{-1/\zeta} \quad \text{if } z > u$$

where Y denotes the observed skew surges, and ζ, σ and u are the GPD shape, scale and location (i.e. threshold) parameters.

The joint probability analysis assumes independence between skew surge and peak tide levels. A comparison between these two components at all gauge locations reveals this assumption to be correct. **Figure A3.6** shows this independent relationship for an example location.

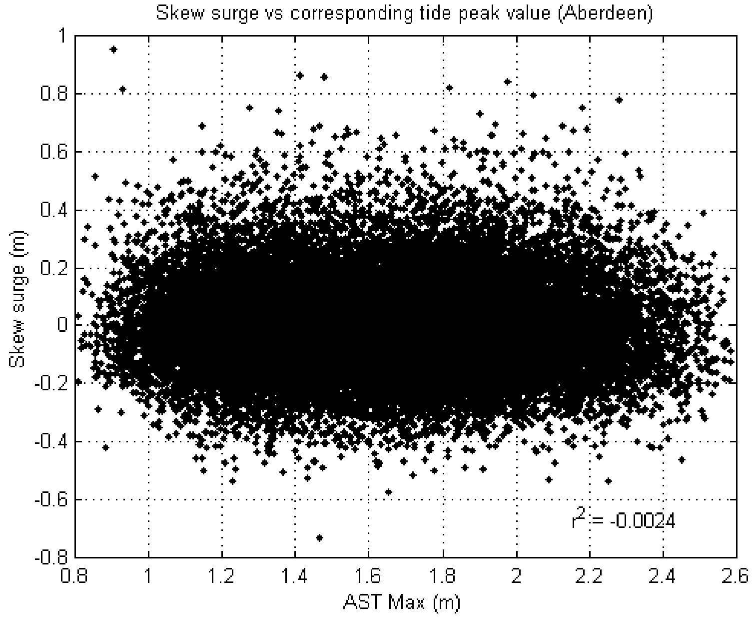


Figure A3.6: Skew surge versus peak tide level

A3.4.3 Total Sea Level Dependence

The duration of storm surges can encompass multiple high tides. This means that there may be a degree of dependence between extreme skew surge levels in the tide gauge record, e.g. two extreme skew surge level observations may have occurred during the same storm. Therefore a correction factor, termed the extremal index, θ, was derived to account for this dependence in the calculation of return period. The reciprocal, $\theta^{-1}(x)$, is the mean cluster size of independent sea-level tidal events that exceed the level x. Essentially, the extremal index reduces the number of observed high tides per year to a value representing the number of independent high tides per year. For extreme sea levels of interest, values of θ were effectively equal to 1 at all gauge locations.

A3.4.4 Return Period Calculation

The final process performed was the expression of the probability distribution of total sea levels in terms of return periods. The return period, T(x), was calculated using the formula,

$$T(x) = \frac{1}{N\ \Theta(x)\ [\ 1\text{-}F_{TSL}(x)]}$$

where N is the number of tides per year.

This method was used to generate the following return period extreme sea levels:

- 1, 2, 5, 10, 20, 25, 50, 75, 100, 150, 200, 250, 300, 500, 1,000, 10,0000

A3.4.5 Smoothing of the GPD Tail Parameter

For a number of sites, the growth rate from low to high return periods (100% to 0.01% annual probability) was implausibly steep compared to the observed data. This implies that there is no limit to the amount of surge which in practice is not the case. **Figure A3.7** shows an example of this unusually steep growth to lower probability (higher return periods) at Hinkley Point.

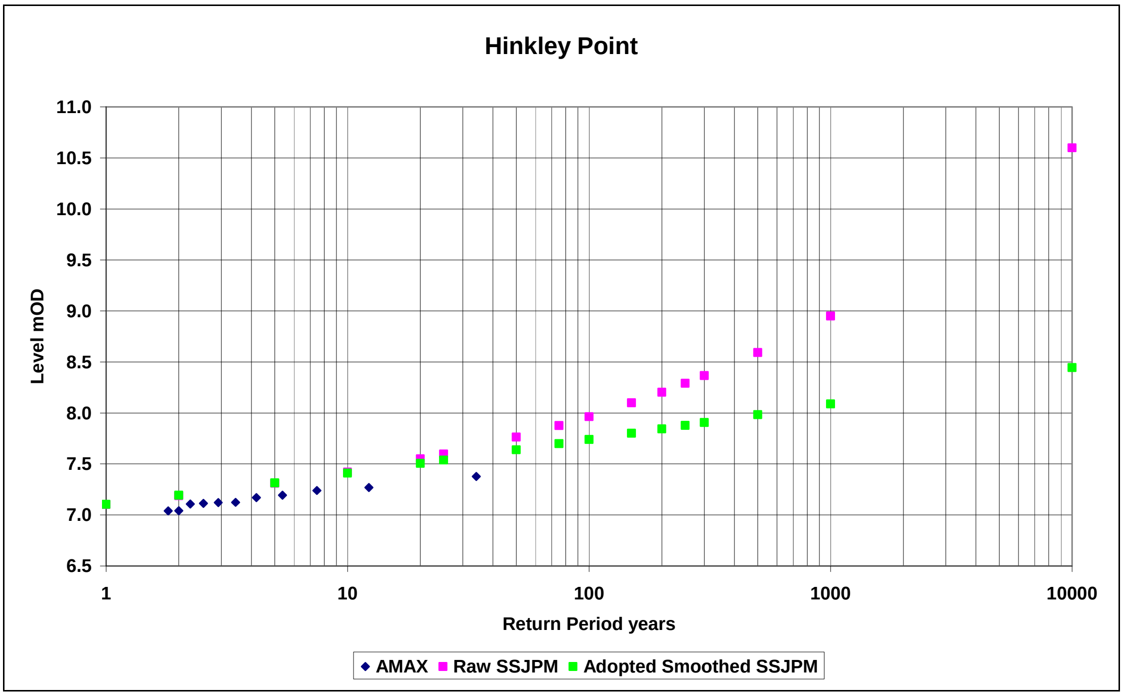


Figure A3.7 Steep growth curve at Hinkley Point

Conversely at other sites the growth curve was unusually low compared to the observed data. This is of particular concern as extreme sea levels are often used as a boundary condition for flood risk assessment and coastal design. The use of levels below the observed data could have significant adverse consequences, such as in the design of defences. **Figure A4.8** shows this unduly low growth curve at Portsmouth.

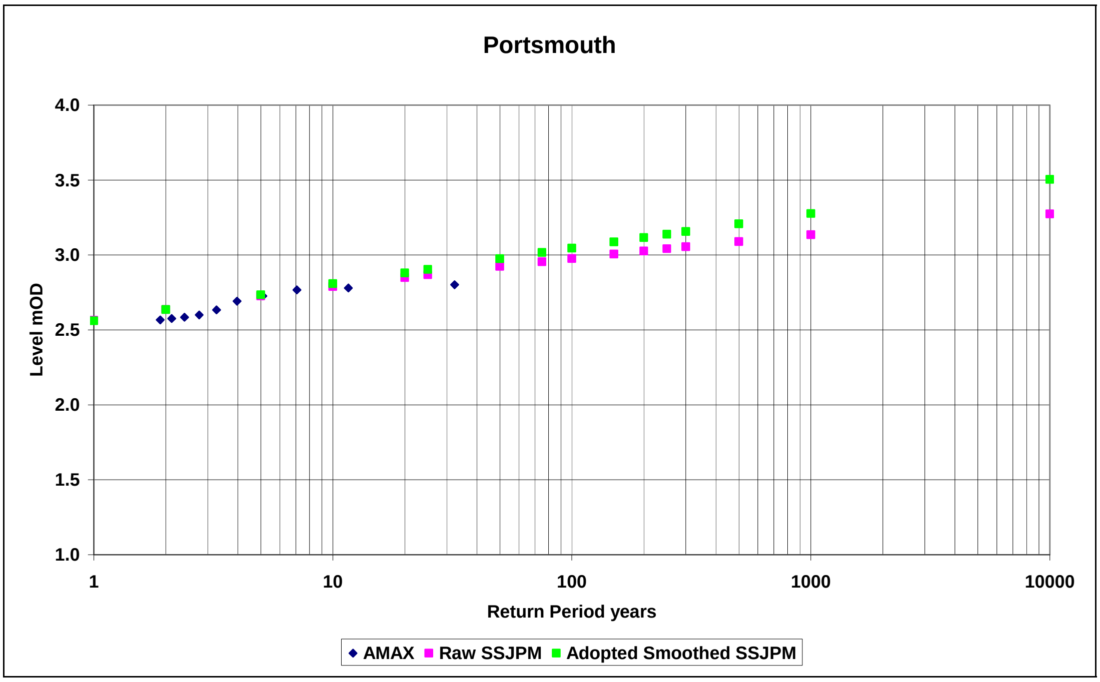


Figure A3.8 Low growth at Portsmouth

For sites where these problems existed, a smoothing of the GPD tail parameters was selected as a suitable method to correct this implausible behaviour of the growth curve at the lower probabilities (higher return periods). As mentioned previously the parameters of shape and scale define the GPD and were determined from the extreme value data using the method of maximum likelihood.

We have smoothed the shape parameter of the GPD tail for some sites using four neighbouring sites. This process involves weighting each neighbour according to the length of data. Therefore this gives more credence to sites with longer tide gauge records.

The extreme skew surge process is likely to change smoothly over space in a non-specific way. However when estimating the parameters of the tail of the skew surge distribution, using the data at each site, we introduce differential levels of noise due to the variability of estimation. The variance is a function of the length of the data series. If all sites had identical distributions of skew surge then the correct thing to do is to average over sites, recognising that some estimates carry less/more information than other sites, thus the reason for a weighted average.

The estimates of the skew surge parameters vary much more than the true parameters do over sites, so some form of averaging to the mean is required. However, as we believe the "mean" is itself spatially varying, as the distributions change along coastlines, it is necessary to smooth to the mean locally, using only sites in a neighbouring window of sites.

This method does not, however, consider the geography. Therefore we have applied constraints, based on geographical location, at the following boundaries:

- Atlantic Ocean and Bristol Channel
- North Sea and English Channel
- North Sea and Atlantic Ocean

A3.4.6 Lowestoft

Lowestoft is an example where neither the 'raw SSJPM' nor smoothing of the GPD tail was appropriate. The raw SSJPM produced an implausibly steep growth curve and the smoothing, using the GPD tail characteristics of neighbouring sites, produced dangerously low levels. The higher probability (lower return period) levels matched well with the observed data.

Therefore the 1-year level produced by the 'raw SSJPM' was retained. Instead of using the GPD tail characteristics of neighbouring sites, we instead adopted an approach using the trend line of growth to lower probabilities. This approach involved using the growth curves from Southend and Felixstowe and Immingham and Cromer. These are the two neighbouring pairs of primary analysis sites to the south and north of Lowestoft respectively.

Trend lines of the growth from the high probability to low probability were produced from the north and south of Lowestoft. Assuming this trend line reflects the geography of the coastal chainage, moving from the Humber Estuary to the Thames Estuary, it is reasonable to assume that the growth trends will also reflect this geography. **Figure A3.9** shows sea levels (from MHWS to 200-year) and a decrease in level from Immingham to Cromer and from Southend to Felixstowe with a convergence of these trend lines at a chainage which approximately corresponds with Lowestoft. Therefore it is reasonable to expect the trend of growth from Immignham to Cromer and Southend to Felixstowe to follow a similar pattern with a convergence of these trend lines at Lowestoft.

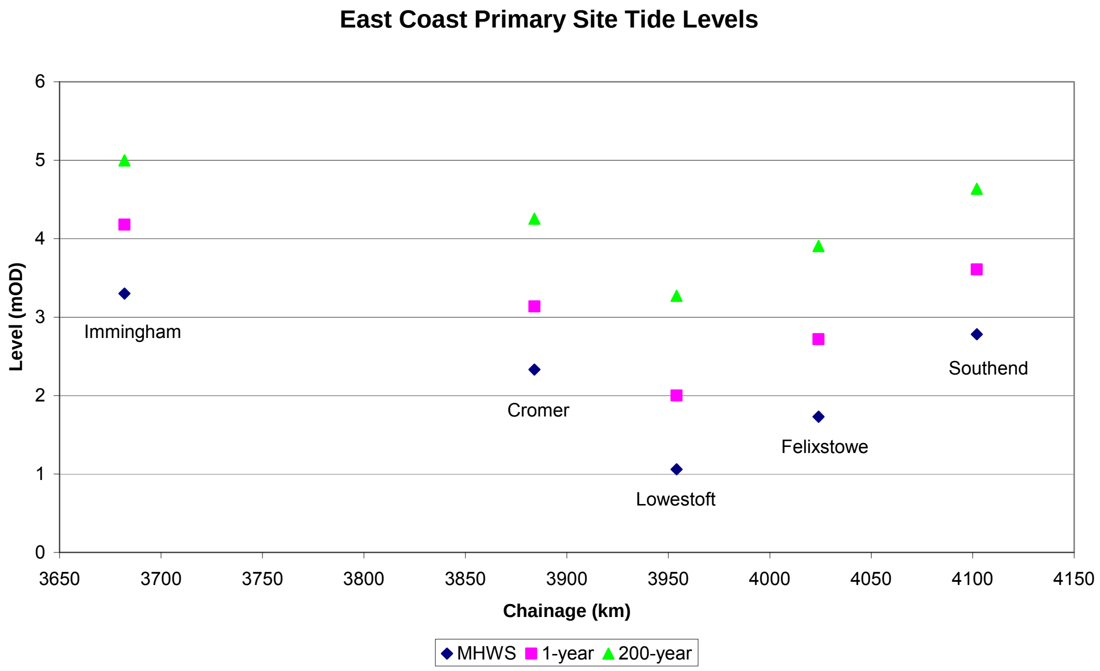


Figure A3.9 Tide levels at East Coast Primary Sites

Figure A3.10 shows the average growth curves for the southern and northern sites relative to Lowestoft growth curve. This shows that the adopted growth curve for Lowestoft matches well with the neighbouring sites.

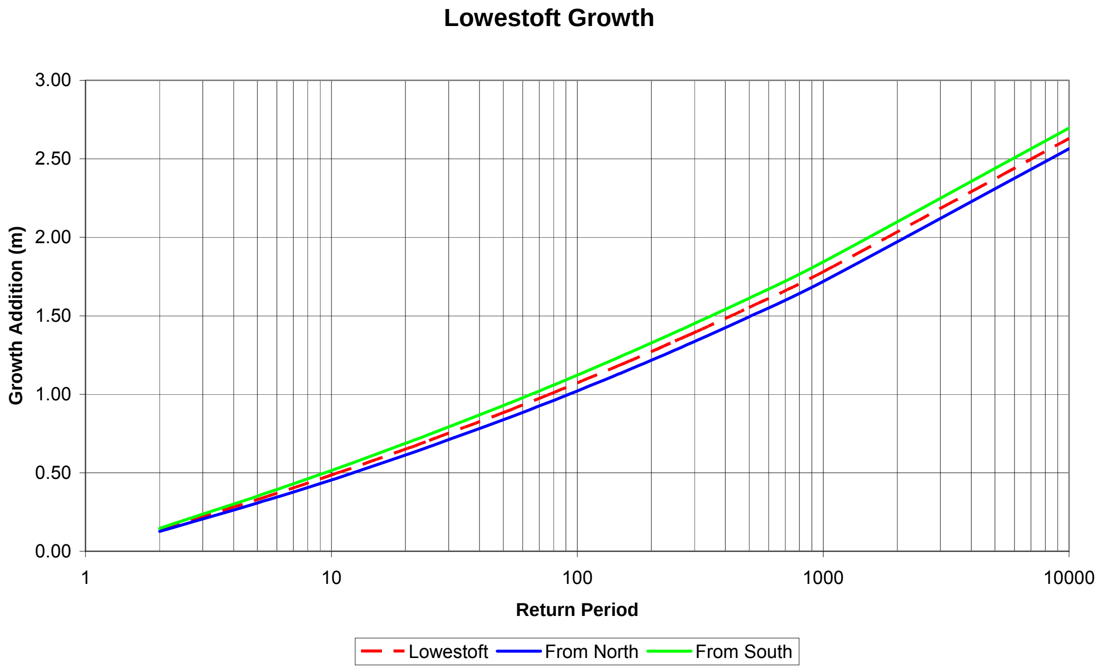


Figure A3.10 Lowestoft growth curves and average neighbouring growth

A3.4.7 Sheerness

The results for Sheerness, both the raw SSJPM and smoothing using neighbouring, were compared with Southend, which was included as a primary analysis site. These sites did not show consistent levels, despite similar positions, albeit on different sides, on the Thames Estuary. To investigate the discrepancy we first compared the MHWS levels. We then selected notable events which were reflected in the gauge records of both sites. For the levels to be appropriate, we would expect the differences to be reflected when comparing these levels. **Table A3.2** presents this comparison. This shows the differences are generally very small, therefore we would not expect the extreme sea levels at Sheerness and Southend to be different.

Table A3.2 Tide Level Comparison at Sheerness and Southend

	Levels (mOD)		
Event	**Sheerness**	**Southend**	**Difference**
10-Dec-65	4.11	4.23	0.12
14-Dec-73	3.97	3.96	-0.02
29-Oct-96	3.89	3.87	-0.01
16-Sep-66	3.70	3.86	0.17
05-Oct-67	3.74	3.83	0.09
28-Jan-94	3.76	3.78	0.02
02-Feb-83	3.78	3.76	-0.02
08-Feb-01	3.74	3.72	-0.01
29-Sep-69	3.76	3.67	-0.09
01-Feb-71	3.69	3.61	-0.09
MHWS	2.77	2.78	0.01

We have therefore selected levels to apply at Sheerness and Southend, based on the best match with the observed data as shown in **Figure A3.11**. The Southend extreme sea levels matched well with the observed data. As a result, extreme sea levels from Southend were applied to Sheerness.

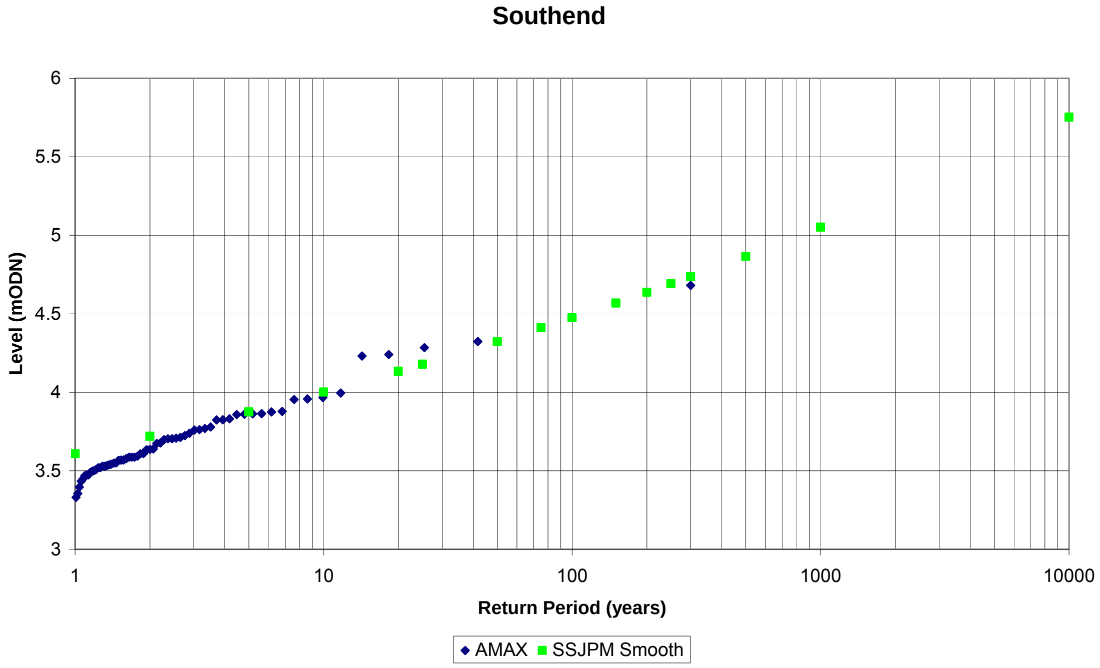


Figure A3.11 Southend SSJPM smoothed levels and Southend AMAX series

Table A3.1 presents the extreme sea levels calculated using statistical analysis as described in Section 3 of the main report. Where there is a departure from the 'raw SSJPM' due to smoothing of the GPD tail parameters using neighbouring sites, or interpolation of the growth curve, reference to the approach used to derive extreme sea levels is provided.

A3.5 Interpolation between Primary Analysis Sites

Numerical models were used to interpolate between primary and supplementary gauge sites to produce extreme sea levels. Model results at primary sites were generally lower than the extreme sea levels calculated using statistical analysis. Consequently, a number of adjustments were required, as outlined below.

A3.6 Adjustment of Model Points

A3.6.1 Primary and Supplementary Sites

At the primary and supplementary gauge sites the results at model points were adjusted to match the tide data produced by the statistical analysis.

A3.6.2 Intermediate Model Points

Model points between primary analysis sites were adjusted using a proportional difference in levels between primary analysis sites, according to the following equations. **Figure A3.12** shows the schematic of this interpolation, which corrects the model point at Intermediate Point (C) using the ratio between the difference in model level and fixed point levels and ratio between fixed point levels.

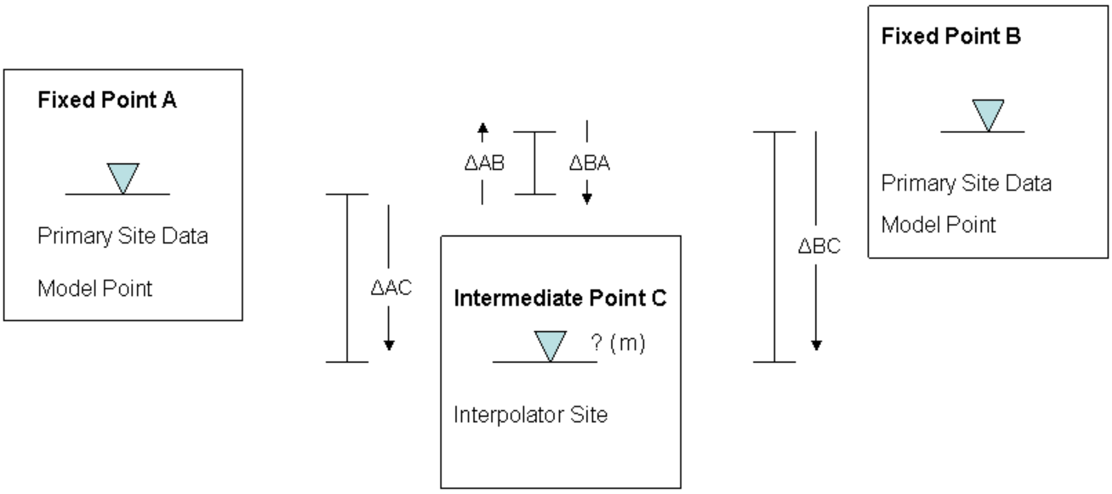


Figure A3.12 Schematic of Interpolation of Model Points between Fixed Points

$$\text{Level}_{\text{(Intermediate Point C)}} = \text{Intermediate Point}_{\text{(C)}} + \alpha + \beta$$

Where

$$\alpha = \frac{\text{Fixed point to intermediate point difference } (\Delta AC)}{\text{Fixed point difference } (\Delta AB)}$$

$$\beta = \frac{\text{Fixed point to intermediate point difference } (\Delta BC)}{\text{Fixed point difference } (\Delta BA)}$$

The concept behind smoothing in this way is to take advantage in change in physical tidal processes moving around the coast which, in principle, are represented by the numerical modelling. This is preferred to interpolating using only distance, which does not represent the physical processes.

It is important that the extremes simulated by the numerical model are statistically consistent with those derived from the observed time series at the same locations. The raw model results were consistently lower at the primary sites compared to the observed data at these locations. Therefore corrections were applied for levels at these sites. Extreme sea level values for the model nodes closest to the primary sites were corrected to accord with those given by the SSJPM statistical analysis.

A3.7 Coastal Trend Line

A3.7.1 Coastal Chainage

A coastal trend line was set up around the UK with chainages running clockwise from an origin at Newlyn. The trend line is set a little offshore from the coast so distances do not become unduly distorted by small coves and promontories, as would be the case if mean low water mark was used for example. Chainage points are set at 2km intervals. The trend line is shown on **Figure 1.1** to **Figure 1.6**.

A3.7.2 Interpolation between Adjusted Points

The corrected model node sea level values, as noted in Section 3.6, were applied to their respective nearest coastal chainage points. An interpolation was then made between these adjusted points, using the trend in relationship between the MHWS and model 1-year level to guide the 1-year values. The subsequent growth to higher return periods was taken as varying linearly between the adjusted model points.

A3.7.3 Trend Line at Liverpool Bay

The trending using the Liverpool smoothed SSJPM results did not match the adjacent coastal chainages despite matching well with observed data. Therefore standalone values based on the SSJPM analysis are provided for Liverpool, Gladstone Dock, as shown in **Table A3.3**. The Liverpool data was removed from the interpolation process between primary sites to ensure a smooth trend along the coast.

Table A3.3 – SSJPM Results for Liverpool, Gladstone Dock

Return Period (years)	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1000**	**10000**
Sea Level (mOD)	5.51	5.62	5.77	5.90	6.04	6.09	6.25	6.35	5.51	5.62	5.77	5.90	6.04	6.09	6.25	6.35

As a result, statistical analysis was undertaken using data from Hilbre Island. The growth curve derived by statistical analysis undertaken at Hilbre Island matched well with observed data therefore was deemed an appropriate substitute for the Liverpool gauge data in the interpolation process.

A3.8 Adjustments at Intermediate Model Points

Tide gauge data was obtained for thirty six sites (here termed the secondary sites) at intermediate locations between the primary sites; these are shown in **Figure 2.1**. The sea level values along the coastal chainage line, derived as in **Section 3.7**, were compared with event records from these secondary sites. The purpose of this comparison was to look for consistency between the corrected model output levels and intermediate observed levels using two criteria:

- To identify how the lower end (below ten year return period) compared with return periods implied by the data.
- To identify, for widespread events, whether the return period of the event was broadly similar at the primary sites and the intermediate sites, for example the January 1953 event record at Wells.

For sites where these comparisons resulted in no obvious discrepancy, there was no basis to alter the intermediate values between the primary sites.

For sites where discrepancies were identified, comparative sea levels were obtained for a wide range of notable events as recorded at the secondary site and its surrounding primary sites. The sites where this was undertaken are listed below:

- Uphill
- Llanelli
- Fleetwood
- Ramsden Dock, Barrow
- Orkney Islands
- Burgh Sluice
- Wells
- Littlehampton
- Calshot
- Cowes

- Lymington

The aim of this comparison was to identify differences in peak tide levels for these notable events. From this, taking into account some variation, clear trends of a sea level relationship were identified between the secondary and primary sites for extreme events. The 1-year level at the secondary site was made consistent with the primary site 1-year level by adding or subtracting this ‘event difference’ relationship. Return periods of notable events now became more consistent between adjacent sites and gave a better fit to the observations at the secondary site and its surrounding primary sites. This method gives a more plausible trend of levels around the coast.

For sites where these further adjustments were applied, the growth curve given by the original trending was retained. The reason for this is that there is not enough observed data at the high end of the growth curve for third party sites.

Where sea levels at the secondary sites were adjusted, values at nearby intermediate points between the primary sites also required adjustment to retain a sensible trend in levels along the coastline. This trend was the relationship between MHWS and the 1-year level and gave a better fit to the observations at the secondary sites.

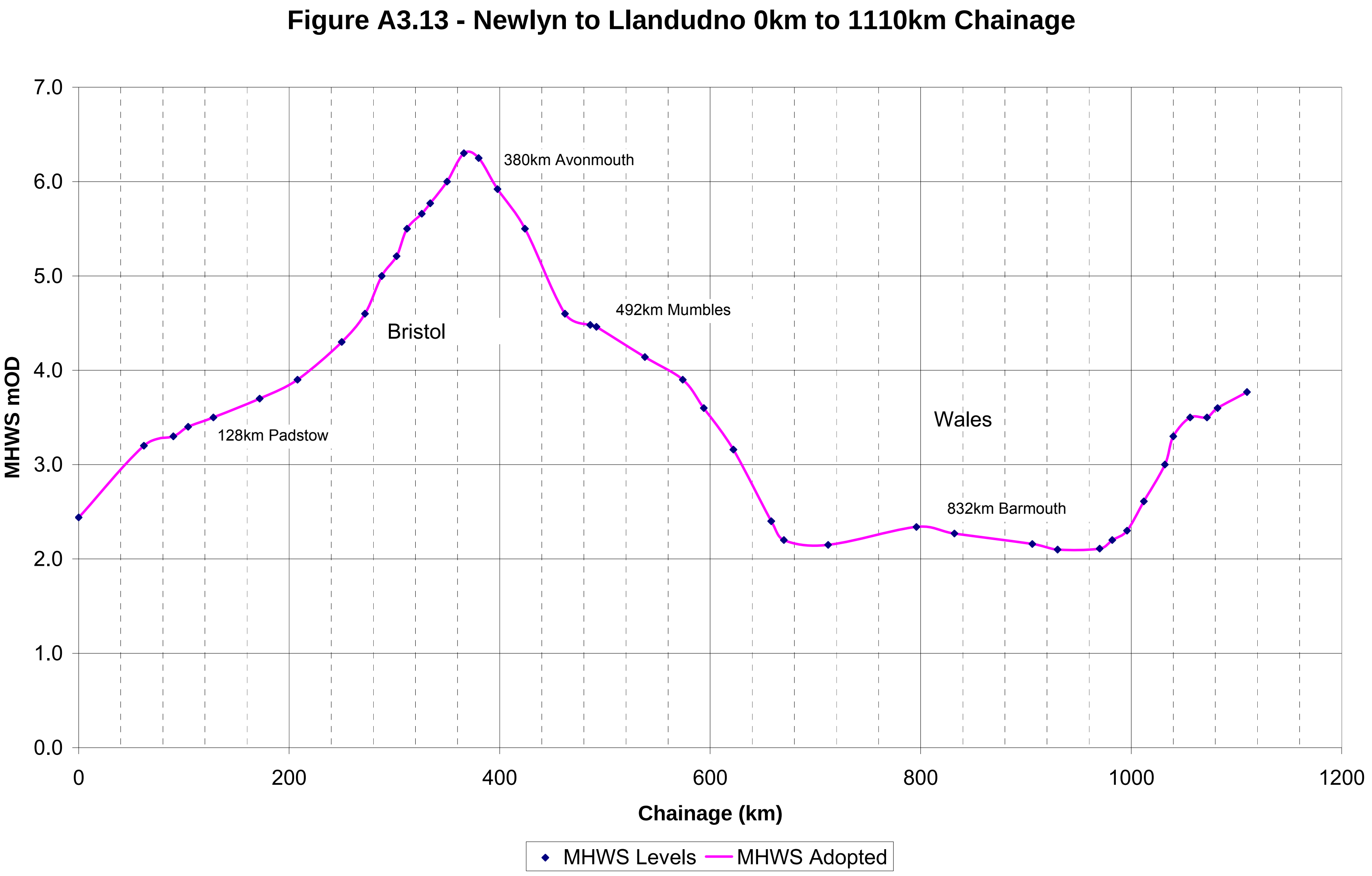


Figure A3.13 - Newlyn to Llandudno 0km to 1110km Chainage
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
MHWS mOD
0
200
400
600
800
1000
1200
Chainage (km)
380km Avonmouth
492km Mumbles
Bristol
128km Padstow
Wales
832km Barmouth
MHWS Levels
MHWS Adopted

Figure A3.14 - Llandudno to Kintyre 1110km to 1972km Chainage

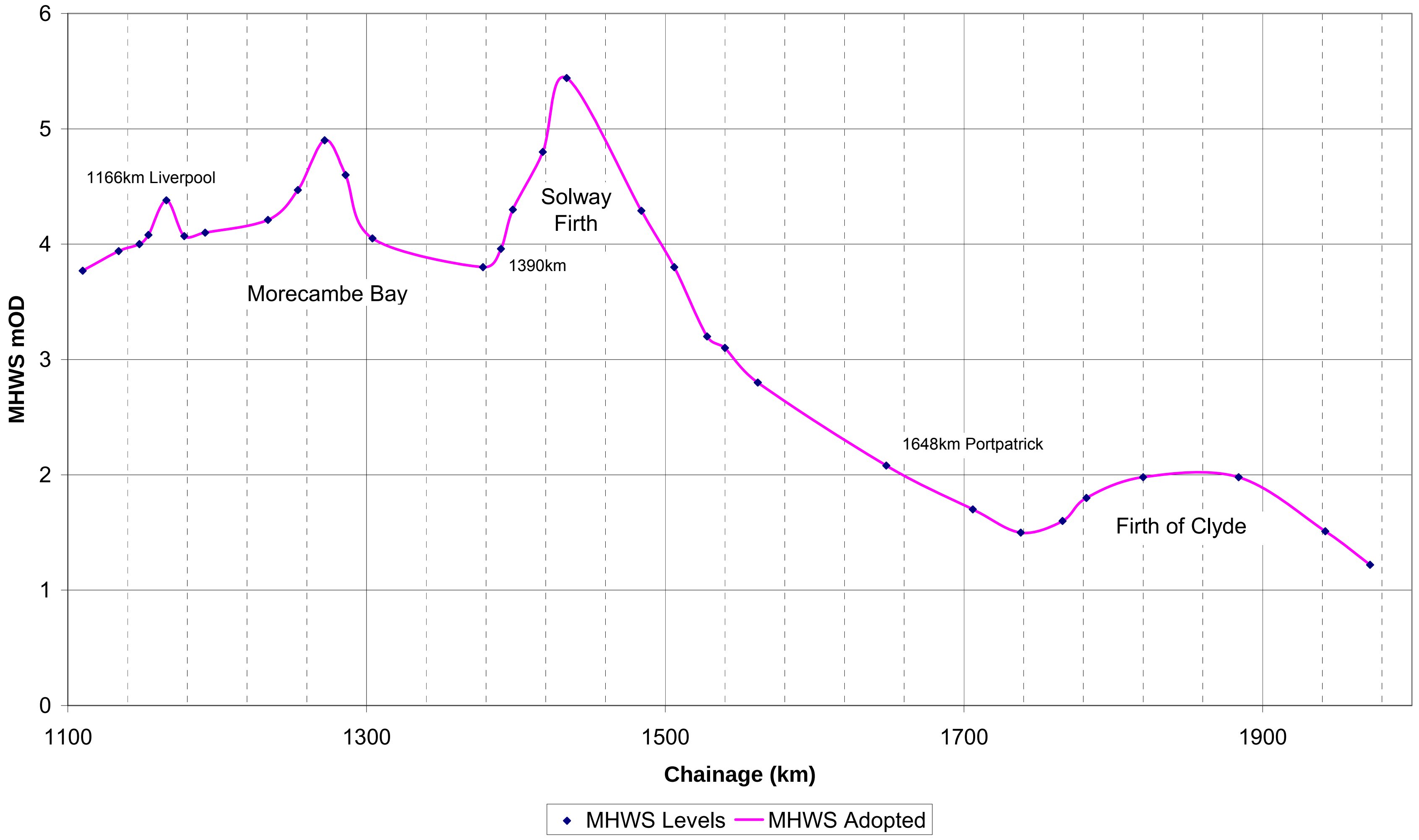


Figure A3.15 - Kintyre to Dunbar 1972km to 3476km Chainage

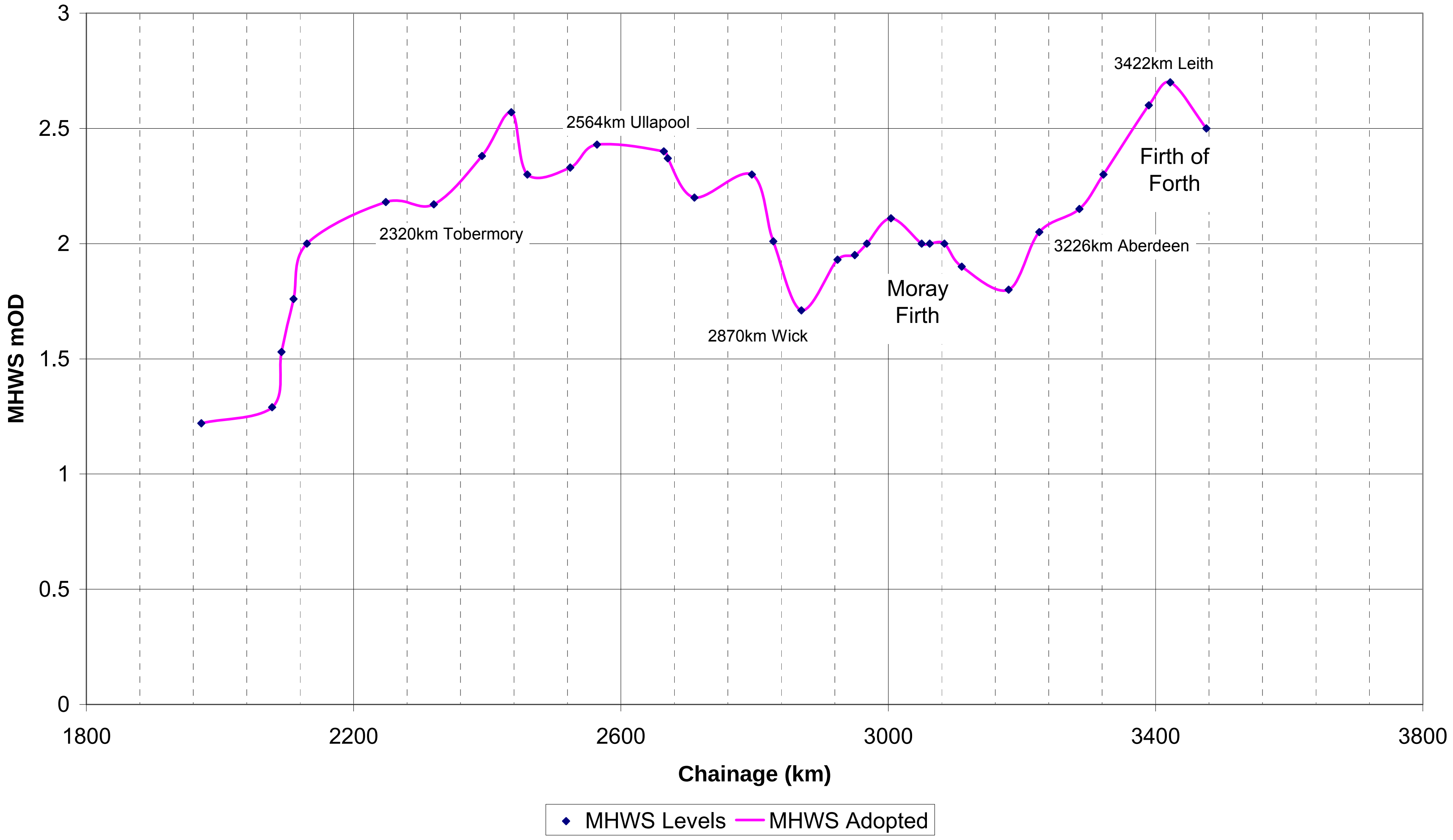


Figure A3.16 - Dunbar to Margate 3476km to 4382km Chainage

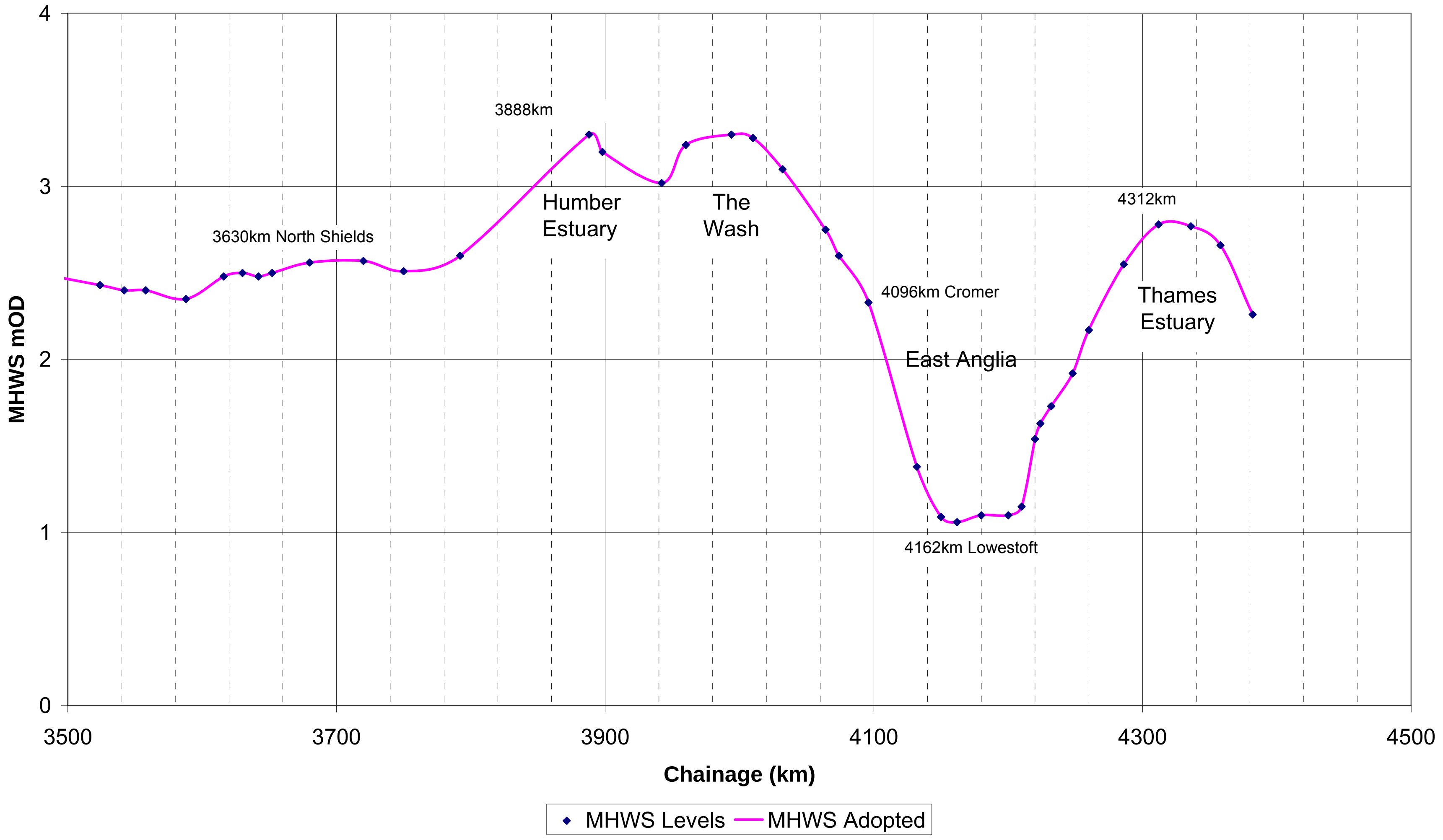
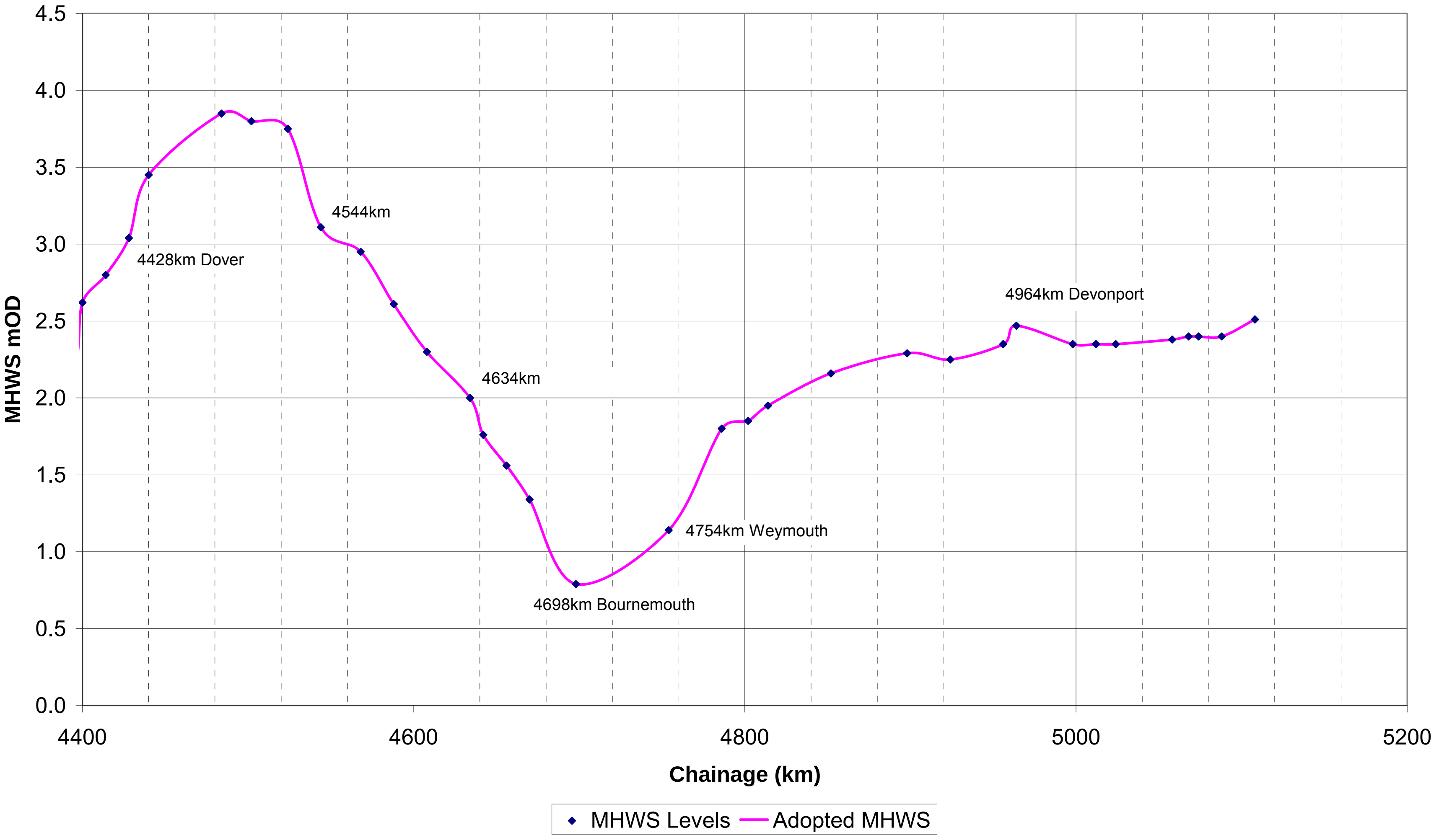


Figure A3.17 - Margate to Porthleven 4382km to 5108km Chainage



Appendix 4 Coastal Modelling

A4.1 Introduction

Primary analysis was undertaken at the Class A and five supplementary sites. In order to provide extreme sea levels for a continuous chainage around the coast of the UK we first used a numerical model to interpolate between the primary analysis sites. This Appendix presents further details of the POL CS3X Continental Shelf Model.

A4.2 POL CS3X Continental Shelf Model

In order to provide estimates of extreme water levels between tide gauge sites and to guarantee a consistent methodology around the entire coastline, including complex topographic regions, we used numerical model hindcast simulations. By using numerical models to interpolate dynamically, the correct spatial behaviour of the tide and storm surges in between tide gauge locations is represented. We used the POL operational tide-surge model at 12 km resolution (CS3X), forced by the ECMWF ERA40 meteorological reanalysis (at 1° resolution) to dynamically interpolate between the estimates of extreme water levels at tide gauge sites. Numerical models tend to underestimate extreme sea levels on average when forced by coarse resolution meteorological data, but nevertheless they provide the correct dynamical response and can thus provide 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 to the observational data and thus is statistically consistent. This has been attempted previously by Flather et al. (1998) who used a depth-averaged tide-surge model of the European continental shelf with a horizontal grid of approximately 35 km, and forced it with the 40-year meteorological reanalysis provided by the Norwegian meteorological institute DNMI (Reistad and Iden, 1995). They then compared the 50-year return period surge elevations with observational data in and found reasonable agreement along the Dutch, German and Danish North Sea coastlines, but a tendency for the model to underestimate the 50-year surge (by 0.3-0.5 m) along the UK's North Sea coastline. We improve significantly upon previous modelling work in this study where we use the 12km resolution operational surge model of the UK continental shelf (see **Figure A4.1**) forced by the ERA40 dataset (Uppala et al., 2005). This re-analysis, provide by the European Centre for Medium range Weather Forecasting (ECMWF) spans the period 1960-2001 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). POL numerical models used for surge prediction have been running 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 northwest 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 one hour intervals. Tidal input is supplied at the lateral open boundaries of the model to support tide-surge interaction (e.g. Horsburgh and Wilson, 2007). Tidal input at the model open boundaries consists of the largest 26 constituents.

Validation of the operational model is performed monthly by comparison with observed sea level data from the UK national tide gauge network (see http://www.pol.ac.uk/ntslf/surgemonthlyplots). Modelled surge residuals over the entire re-analysis period were derived by subtracting a tidal simulation from one forced by both tide and the meteorological reanalysis.

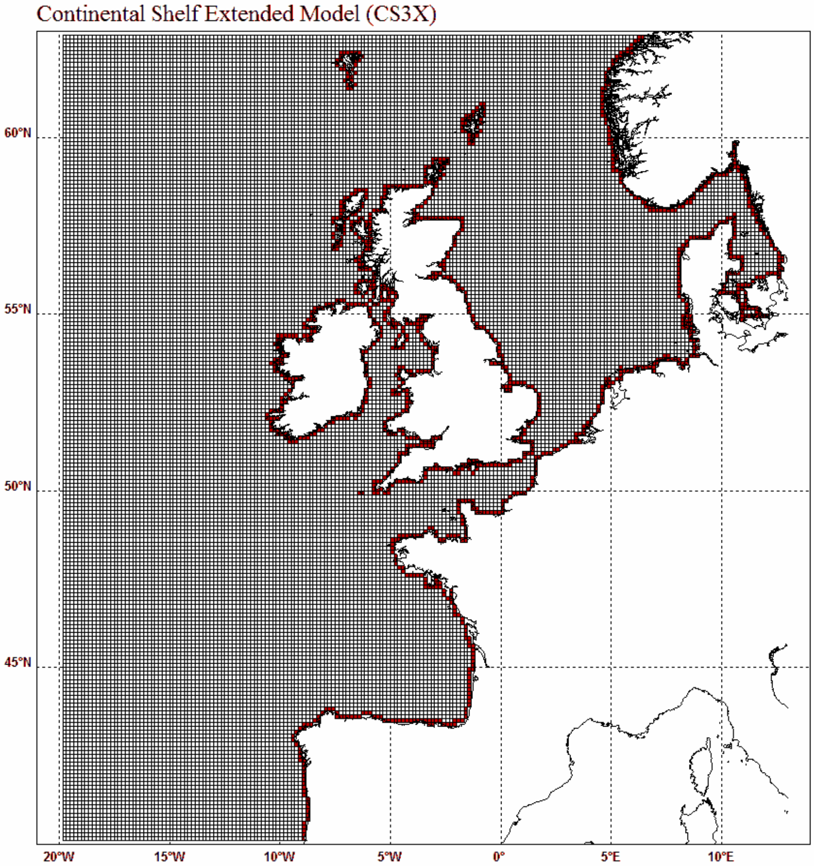


Figure A4.1. POL CS3X shelf wide tide-surge model domain

Model estimates at all coastal locations (extracted from the grid in **Figure A4.1**) were derived using the Skew Surge Joint Probability Method (SSJPM). The return levels (at specified return periods) were then corrected using a weighted interpolation where the weighting factors themselves were derived from a comparison of observed and modelled 1-year return levels: this ensures that the spatial properties of the tide and storm surges influence the correction more than mere distance. The UK national tide gauge network (see http://www.pol.ac.uk/ntslf/networks.html) is sufficiently dense that the majority of model cells on the coastal mainland automatically fall between two national tide gauges, with the exception of the north coast of Devon and parts of the English Channel. To improve the results further we introduce data from Environment Agency tide gauges at Padstow and Exmouth; former Class A tide gauge data at Moray Firth; a combination of tide gauge data from POL, Port of London Authority and Environment Agency for Southend and Hilbre Island tide gauge data from BODC. Extreme sea levels from these locations were estimated using the same statistical methods as for the Class A sites. Those return levels were then used as further calibration for the numerical model results.

A4.3 JBA North East Irish Sea Model

A separate, higher resolution model has been 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 has been used to represent the localised wetting and drying processes more accurately than POL's larger 12km resolution model. This model, run by JBA Consulting, is a 2D depth-averaged version of the Princeton Ocean Model (Blumber, 1987). Like the POL 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 is run twice for the period of the ERA40 data in order to produce a hindcast data set of tidal levels and a data set of total sea levels (including both tidal and meteorological forcing). These two data sets 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 which has a variable resolution of approximately 1000m 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 POM configuration of the Continental Shelf that is of equivalent design to the POL 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 inter-tidal areas.

A4.4 References

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Appendix 5 Comparison of Results with Observed Values

A5.1 Introduction

Results were compared with observed data at primary analysis sites. This appendix shows the results of the statistical analysis at the primary sites compared with annual maxima (AMAX) series, the latter plotted using Gringorten's method.

AMAX were calculated using the highest recorded in each annual data series.

Table A5.1 presents the extreme sea levels calculated using the skew surge joint probability statistical analysis as described in **Section 3** of the main report. The approach used for the growth to longer return period extreme sea levels is provided.

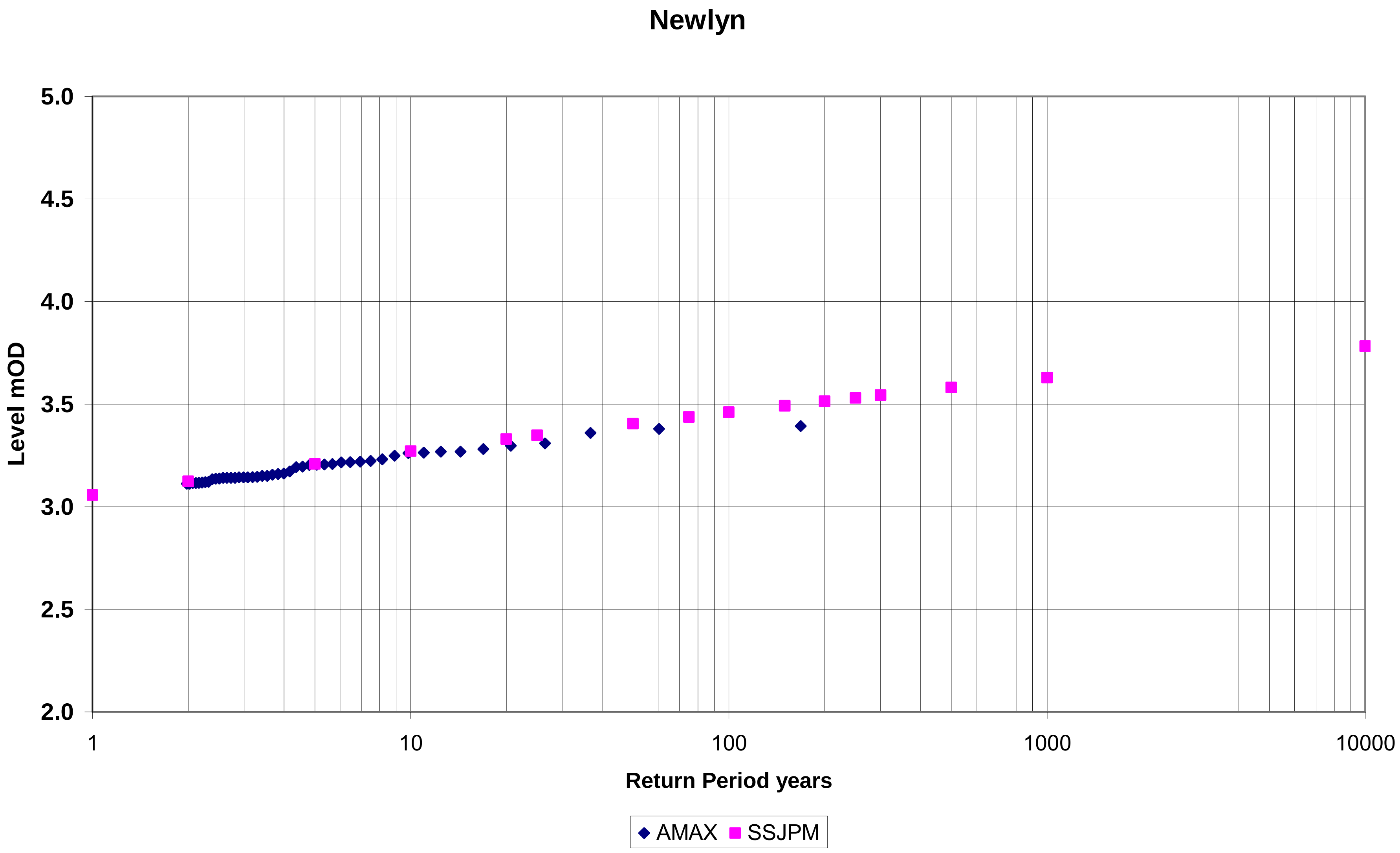
The following figure give plots showing the comparison between the return period sea levels derived from this project and those suggested by the annual maxima series alone.

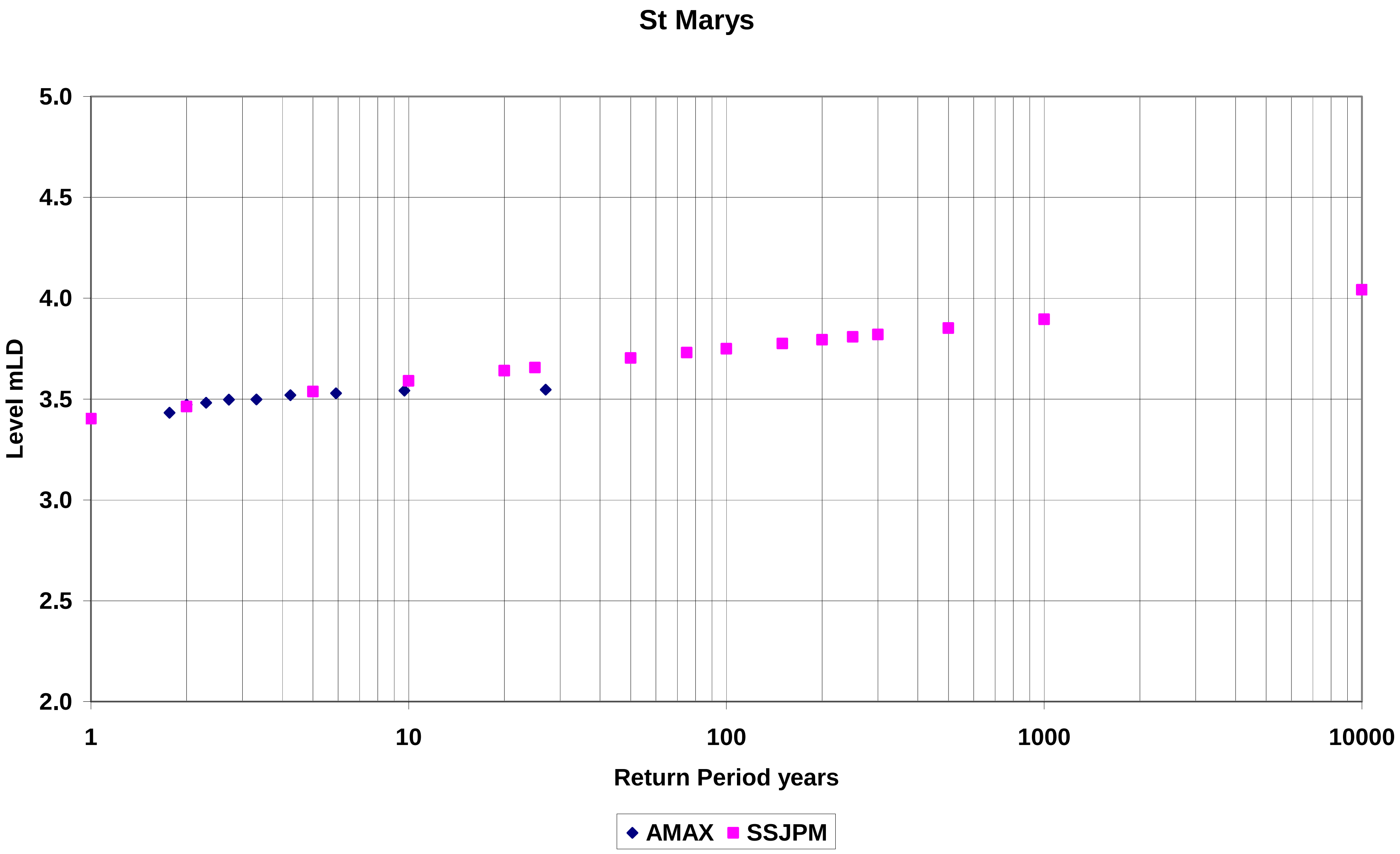
Table A5.1

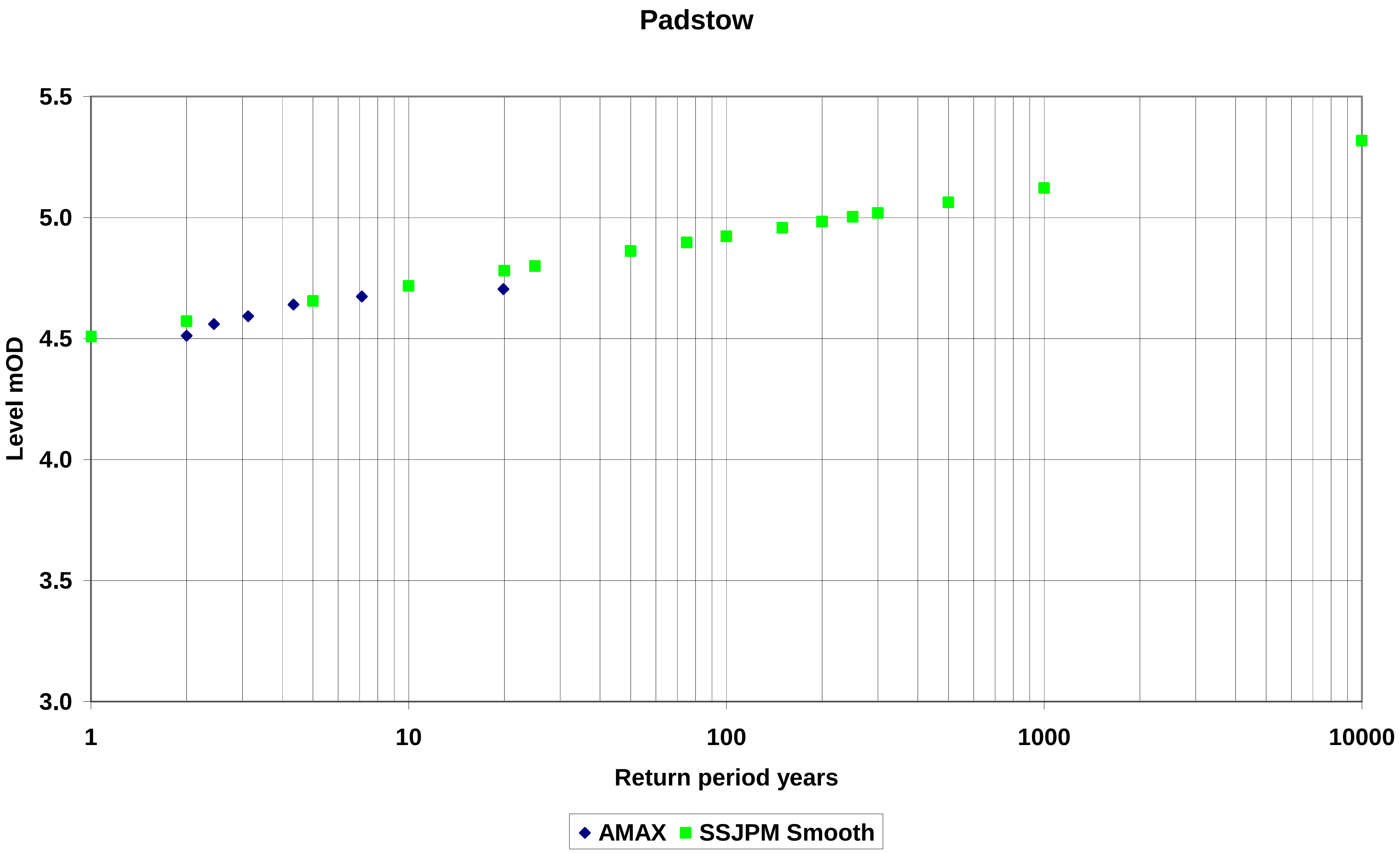
		Return Period Levels at Primary Sites (mOD except where stated) Note 1 – Levels referenced to Local Datum																
Site	**Chainage (km)**	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**	**Chosen Method**
Newlyn	0	3.06	3.12	3.21	3.27	3.33	3.35	3.41	3.44	3.46	3.49	3.51	3.53	3.54	3.58	3.63	3.78	SSJPM
St Mary's (Note 1)	N/A	3.40	3.46	3.54	3.59	3.64	3.66	3.70	3.73	3.75	3.78	3.79	3.81	3.82	3.85	3.90	4.04	SSJPM
Padstow	128	4.51	4.57	4.65	4.72	4.78	4.80	4.86	4.90	4.92	4.96	4.98	5.00	5.02	5.06	5.12	5.32	SSJPM Smoothing
Ilfracombe	250	5.39	5.46	5.55	5.62	5.69	5.72	5.79	5.83	5.86	5.91	5.94	5.96	5.98	6.04	6.12	6.42	SSJPM
Hinkley Point	326	7.10	7.19	7.31	7.41	7.51	7.54	7.64	7.7	7.74	7.8	7.84	7.88	7.91	7.98	8.09	8.45	SSJPM Smoothing
Avonmouth	380	8.16	8.27	8.43	8.55	8.67	8.72	8.85	8.92	8.98	9.06	9.11	9.16	9.19	9.29	9.43	9.89	SSJPM Smoothing
Newport	398	7.54	7.64	7.78	7.89	8.00	8.04	8.16	8.23	8.28	8.35	8.41	8.45	8.48	8.58	8.72	9.22	SSJPM Smoothing
Mumbles	492	5.47	5.54	5.65	5.74	5.83	5.86	5.95	6.01	6.05	6.11	6.15	6.18	6.21	6.28	6.39	6.77	SSJPM
Milford Haven	622	4.14	4.22	4.33	4.40	4.48	4.51	4.59	4.64	4.67	4.72	4.75	4.78	4.80	4.87	4.95	5.26	SSJPM
Fishguard	712	3.09	3.16	3.24	3.31	3.37	3.40	3.46	3.49	3.52	3.56	3.58	3.60	3.62	3.66	3.73	3.93	SSJPM
Barmouth	832	3.48	3.59	3.73	3.83	3.92	3.95	4.04	4.10	4.13	4.18	4.22	4.24	4.27	4.33	4.41	4.66	SSJPM
Holyhead	1012	3.36	3.44	3.54	3.61	3.68	3.70	3.77	3.8	3.83	3.87	3.89	3.91	3.93	3.98	4.04	4.22	SSJPM
Llandudno	1110	4.74	4.82	4.93	5.01	5.09	5.12	5.20	5.25	5.29	5.34	5.38	5.40	5.43	5.49	5.58	5.89	SSJPM
Hilbre Island	1154	5.28	5.38	5.52	5.62	5.72	5.75	5.84	5.90	5.94	5.99	6.03	6.06	6.09	6.16	6.25	6.55	SSJPM
Port Erin (Note 1)	N/A	3.32	3.41	3.52	3.60	3.68	3.70	3.77	3.81	3.84	3.88	3.90	3.92	3.94	3.99	4.04	4.22	SSJPM
Heysham	1254	5.89	6.01	6.17	6.29	6.42	6.45	6.58	6.65	6.70	6.77	6.82	6.86	6.89	6.98	7.09	7.48	SSJPM Smoothing
Workington	1390	5.10	5.21	5.35	5.46	5.56	5.60	5.70	5.76	5.81	5.87	5.91	5.94	5.97	6.04	6.15	6.47	SSJPM Smoothing
Portpatrick	1648	2.82	2.91	3.03	3.11	3.19	3.22	3.30	3.34	3.37	3.42	3.45	3.47	3.49	3.54	3.61	3.83	SSJPM
Millport	1782	2.65	2.77	2.93	3.06	3.20	3.24	3.38	3.46	3.52	3.61	3.67	3.72	3.76	3.87	4.03	4.60	SSJPM
Port Ellen (Islay)	N/A	1.51	1.61	1.74	1.84	1.93	1.96	2.05	2.10	2.14	2.19	2.22	2.25	2.27	2.33	2.41	2.66	SSJPM Smoothing
Tobermory	2320	3.00	3.11	3.25	3.36	3.47	3.50	3.62	3.69	3.74	3.82	3.87	3.91	3.94	4.04	4.18	4.67	SSJPM
Ullapool	2564	3.23	3.32	3.43	3.51	3.59	3.61	3.69	3.73	3.76	3.79	3.82	3.84	3.86	3.90	3.96	4.13	SSJPM
Stornoway (Note 1)	N/A	2.91	2.98	3.07	3.14	3.21	3.22	3.29	3.32	3.34	3.38	3.40	3.42	3.43	3.47	3.52	3.68	SSJPM
Kinlochbervie	2670	3.19	3.28	3.41	3.51	3.61	3.64	3.74	3.8	3.84	3.90	3.94	3.97	4.00	4.07	4.17	4.51	SSJPM
Lerwick (Note)	N/A	1.52	1.57	1.64	1.69	1.73	1.75	1.79	1.81	1.83	1.85	1.87	1.88	1.89	1.92	1.95	2.06	SSJPM
Wick	2870	2.41	2.48	2.56	2.63	2.69	2.71	2.77	2.81	2.83	2.87	2.89	2.91	2.93	2.97	3.03	3.24	SSJPM
Moray Firth	3012	2.85	2.91	3.00	3.07	3.13	3.16	3.22	3.26	3.29	3.33	3.35	3.37	3.39	3.44	3.51	3.72	SSJPM Smoothing
Aberdeen	3226	2.68	2.75	2.84	2.91	2.97	2.99	3.05	3.09	3.11	3.14	3.17	3.18	3.20	3.24	3.29	3.45	SSJPM
Leith	3420	3.37	3.44	3.54	3.61	3.69	3.72	3.80	3.85	3.88	3.94	3.97	4.00	4.03	4.10	4.20	4.57	SSJPM
North Shields	3630	3.20	3.27	3.38	3.46	3.55	3.58	3.67	3.72	3.76	3.82	3.86	3.90	3.92	4.00	4.11	4.52	SSJPM
Whitby	3720	3.37	3.46	3.58	3.68	3.78	3.81	3.92	3.98	4.02	4.09	4.14	4.17	4.20	4.29	4.41	4.83	SSJPM

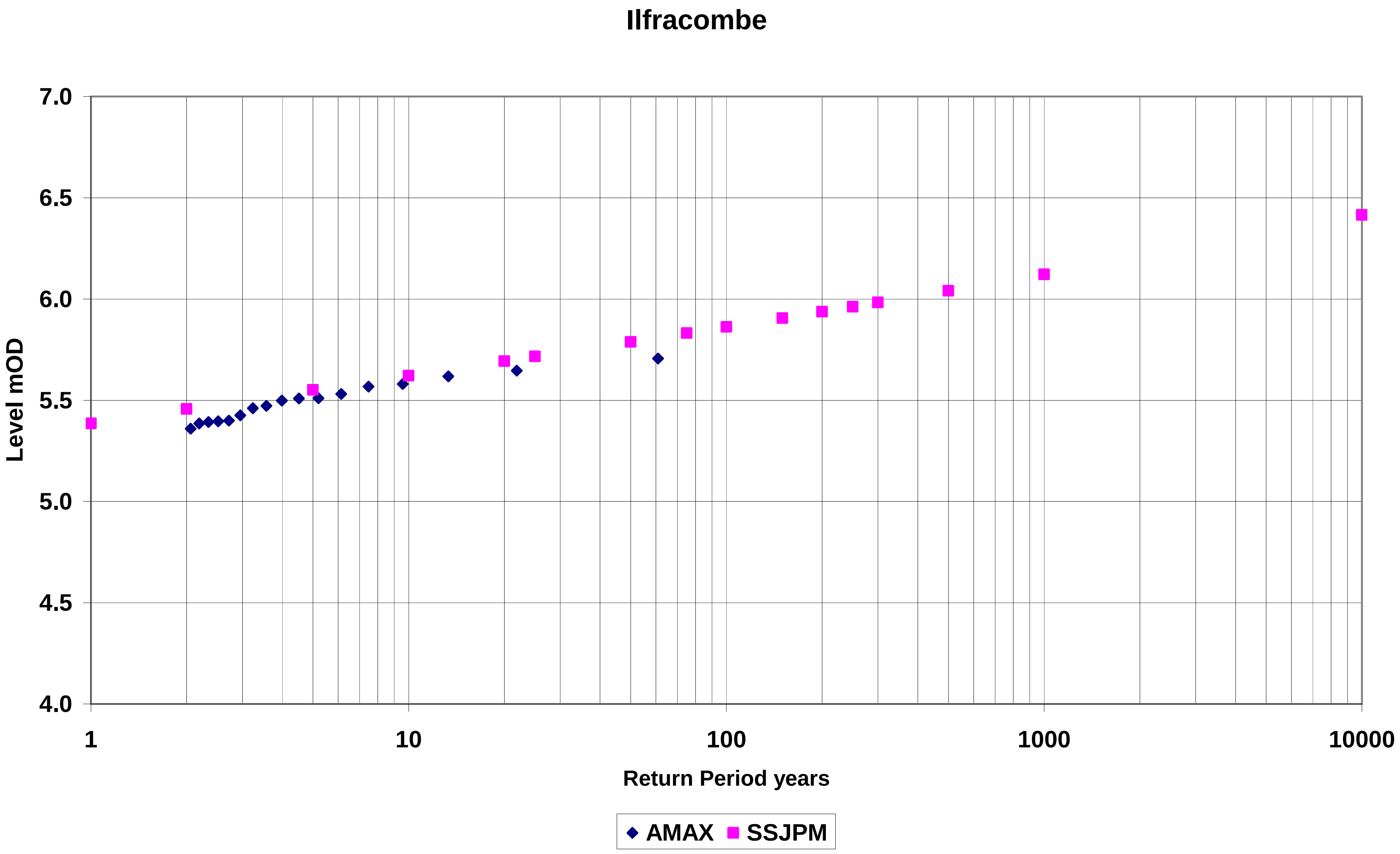
Table A5.1

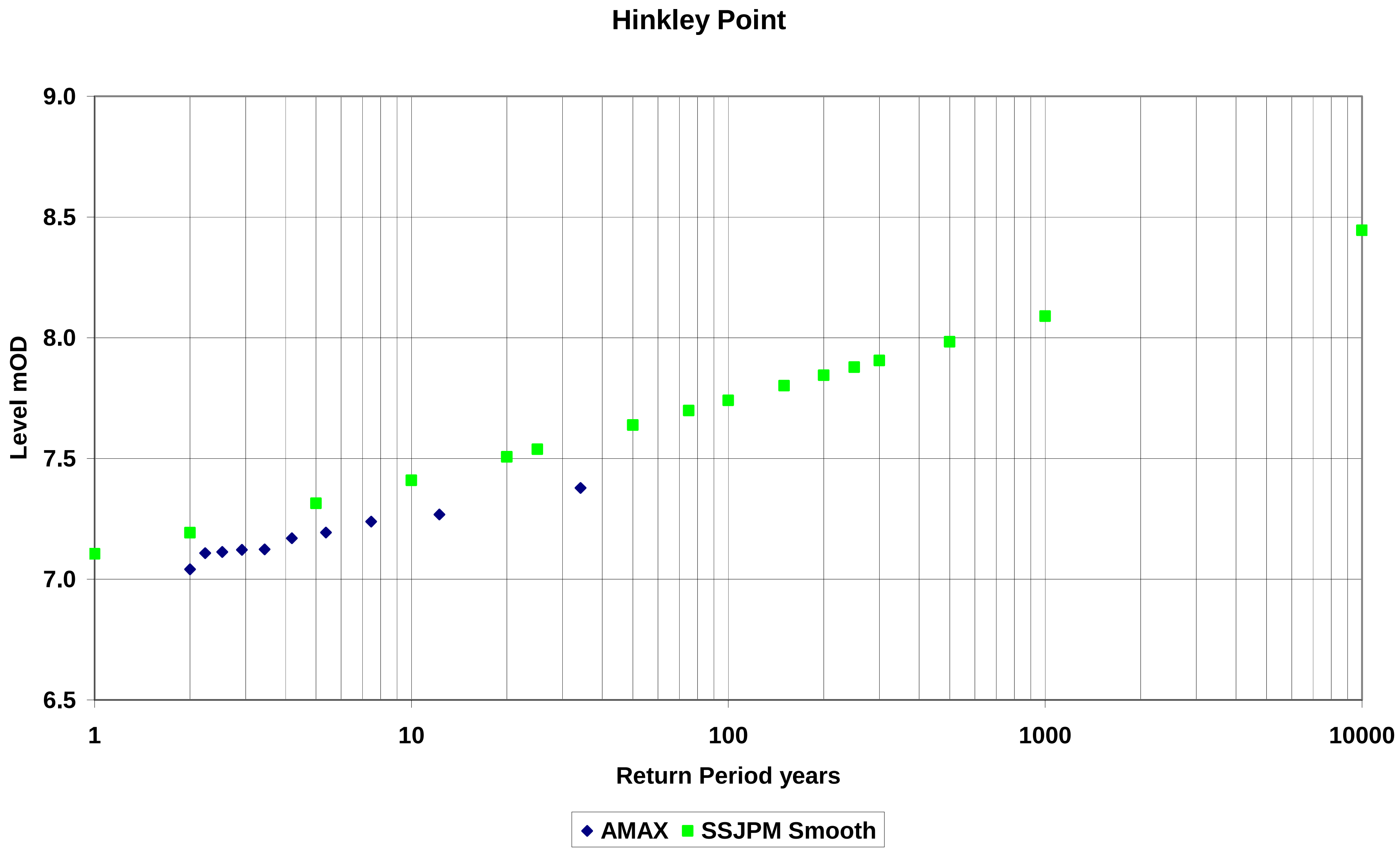
		Return Period Levels at Primary Sites (mOD except where stated) Note 1 – Levels referenced to Local Datum																
Site	**Chainage (km)**	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1,000**	**10,000**	**Chosen Method**
Immingham	3888	4.18	4.28	4.42	4.53	4.64	4.67	4.78	4.84	4.89	4.95	5.00	5.03	5.06	5.14	5.25	5.61	SSJPM
Cromer	4096	3.14	3.26	3.43	3.56	3.71	3.76	3.92	4.01	4.08	4.18	4.25	4.31	4.36	4.50	4.69	5.42	SSJPM Smoothing
Lowestoft	4162	2.00	2.14	2.33	2.48	2.65	2.70	2.88	2.99	3.07	3.19	3.27	3.34	3.39	3.55	3.78	4.63	Interpolated growth
Felixstowe Pier	4232	2.72	2.85	3.03	3.17	3.33	3.38	3.55	3.65	3.72	3.83	3.90	3.97	4.02	4.16	4.37	5.16	SSJPM Smoothing
Southend	4312	3.61	3.72	3.87	4.00	4.13	4.18	4.32	4.41	4.47	4.57	4.64	4.69	4.74	4.87	5.05	5.75	SSJPM Smoothing
Sheerness	4314	3.61	3.72	3.87	4.00	4.13	4.18	4.32	4.41	4.47	4.57	4.64	4.69	4.74	4.87	5.05	5.75	Use Southend
Dover	4410	3.77	3.88	4.03	4.13	4.24	4.27	4.37	4.43	4.48	4.53	4.57	4.61	4.63	4.70	4.80	5.12	SSJPM
Newhaven	4526	3.87	3.94	4.04	4.12	4.19	4.22	4.29	4.34	4.37	4.42	4.45	4.48	4.50	4.56	4.64	4.91	SSJPM
Portsmouth	4616	2.56	2.64	2.73	2.81	2.88	2.90	2.98	3.02	3.05	3.09	3.12	3.14	3.16	3.21	3.28	3.50	SSJPM Smoothing
Bournemouth	4682	1.40	1.47	1.56	1.62	1.68	1.70	1.76	1.79	1.81	1.85	1.87	1.89	1.90	1.94	1.99	2.16	SSJPM
Weymouth	4736	1.77	1.84	1.93	1.99	2.05	2.07	2.14	2.17	2.20	2.23	2.26	2.28	2.29	2.34	2.40	2.59	SSJPM
Exmouth	4836	2.74	2.81	2.90	2.97	3.04	3.06	3.13	3.17	3.20	3.25	3.28	3.30	3.32	3.38	3.46	3.76	SSJPM
Devonport	4950	2.94	3.01	3.10	3.17	3.24	3.26	3.33	3.36	3.39	3.43	3.46	3.48	3.49	3.54	3.60	3.81	SSJPM

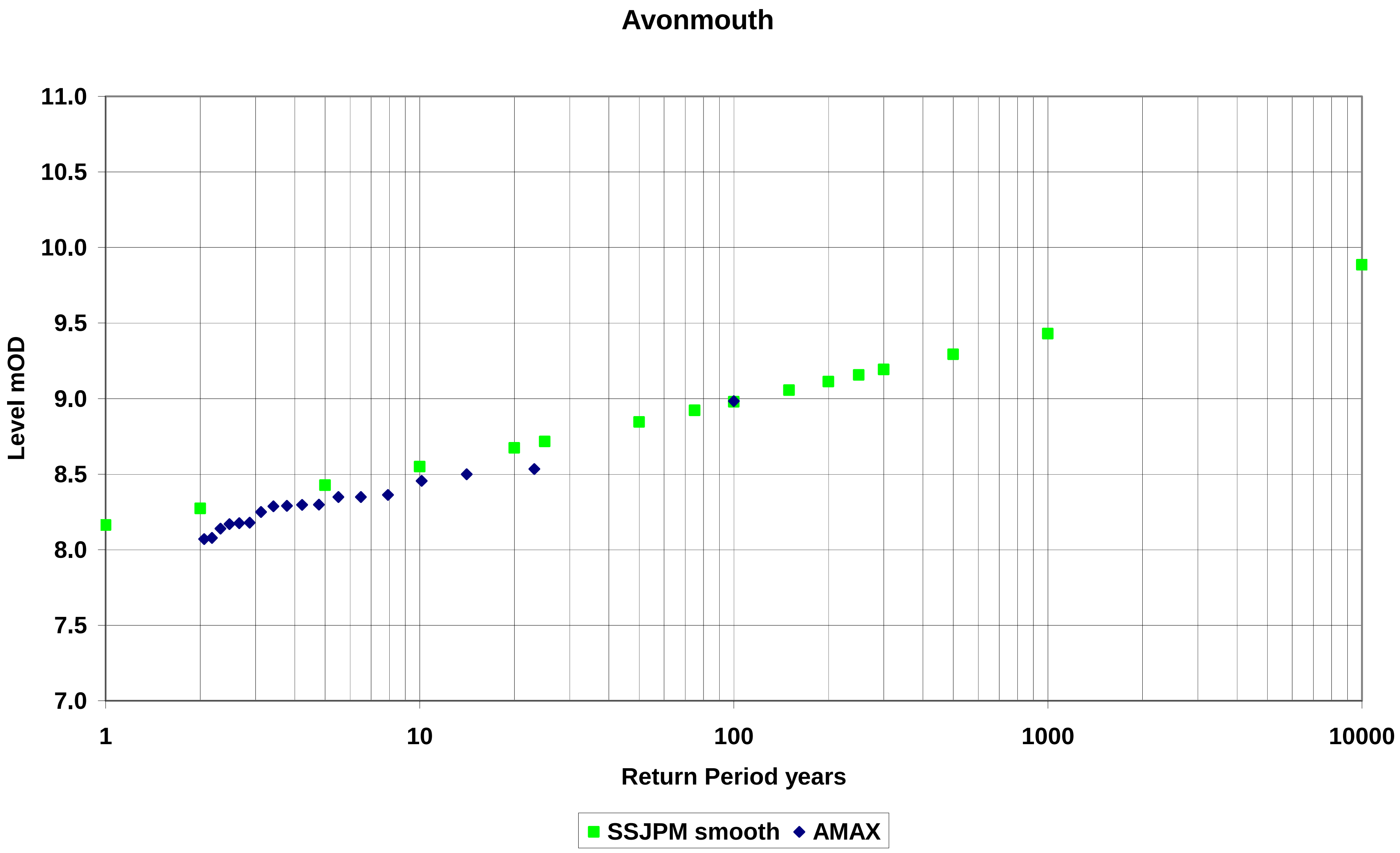

Newlyn
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

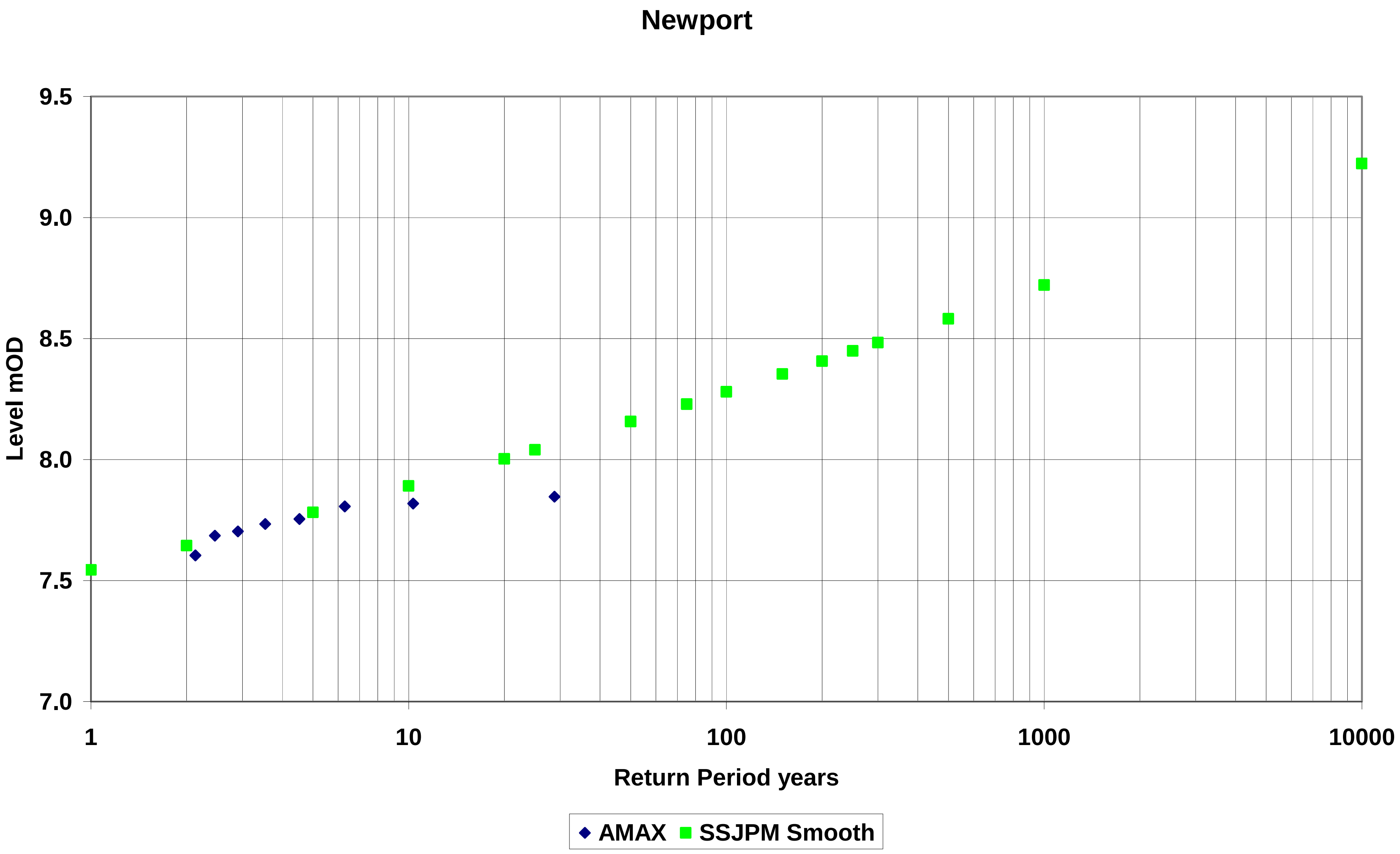

St Marys
Level mLD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM


Padstow
5.5
5.0
4.5
4.0
3.5
3.0
Level mOD
1
10
100
1000
10000
Return period years
◆ AMAX
🟩 SSJPM Smooth

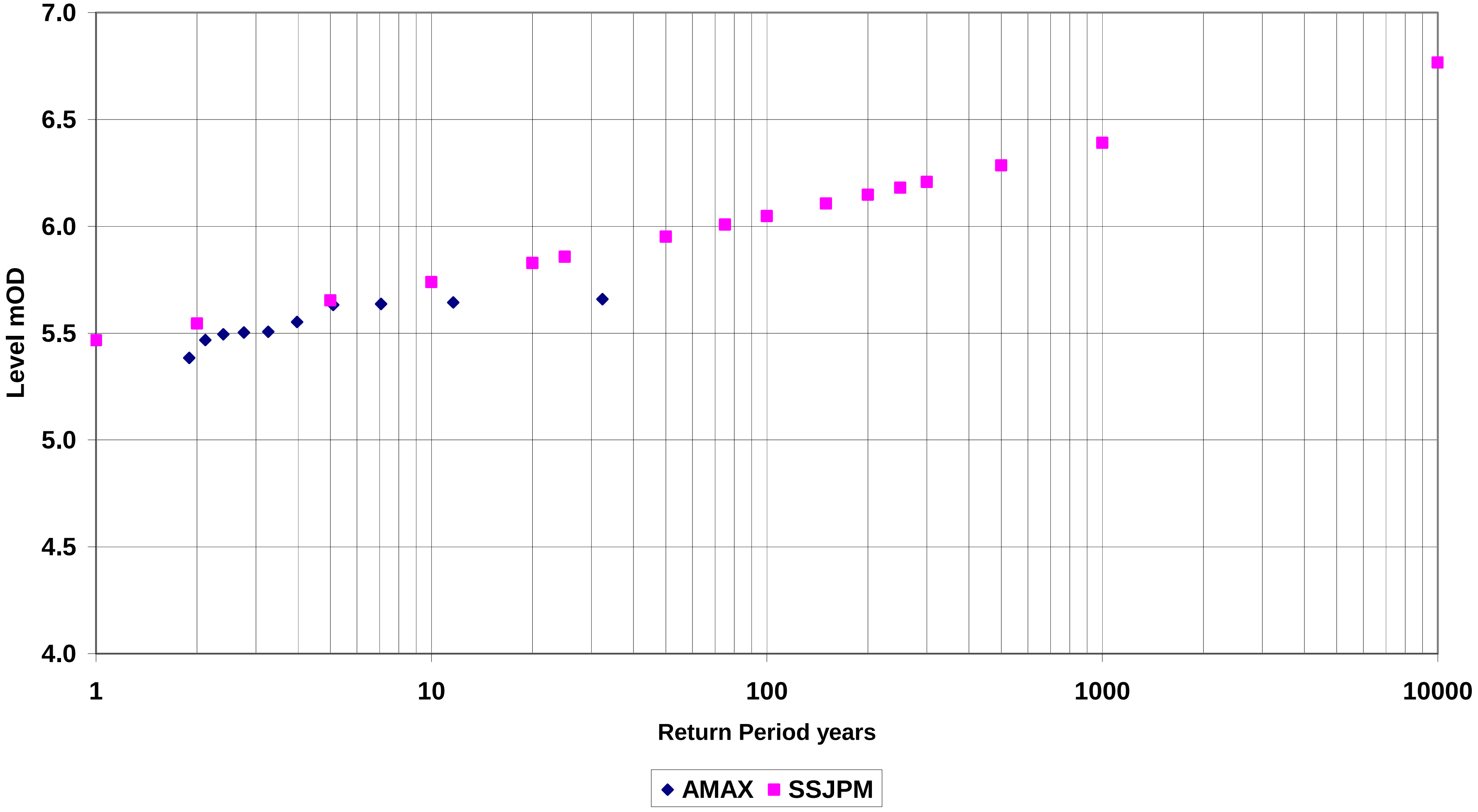

Ilfracombe
Level mOD
7.0
6.5
6.0
5.5
5.0
4.5
4.0
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

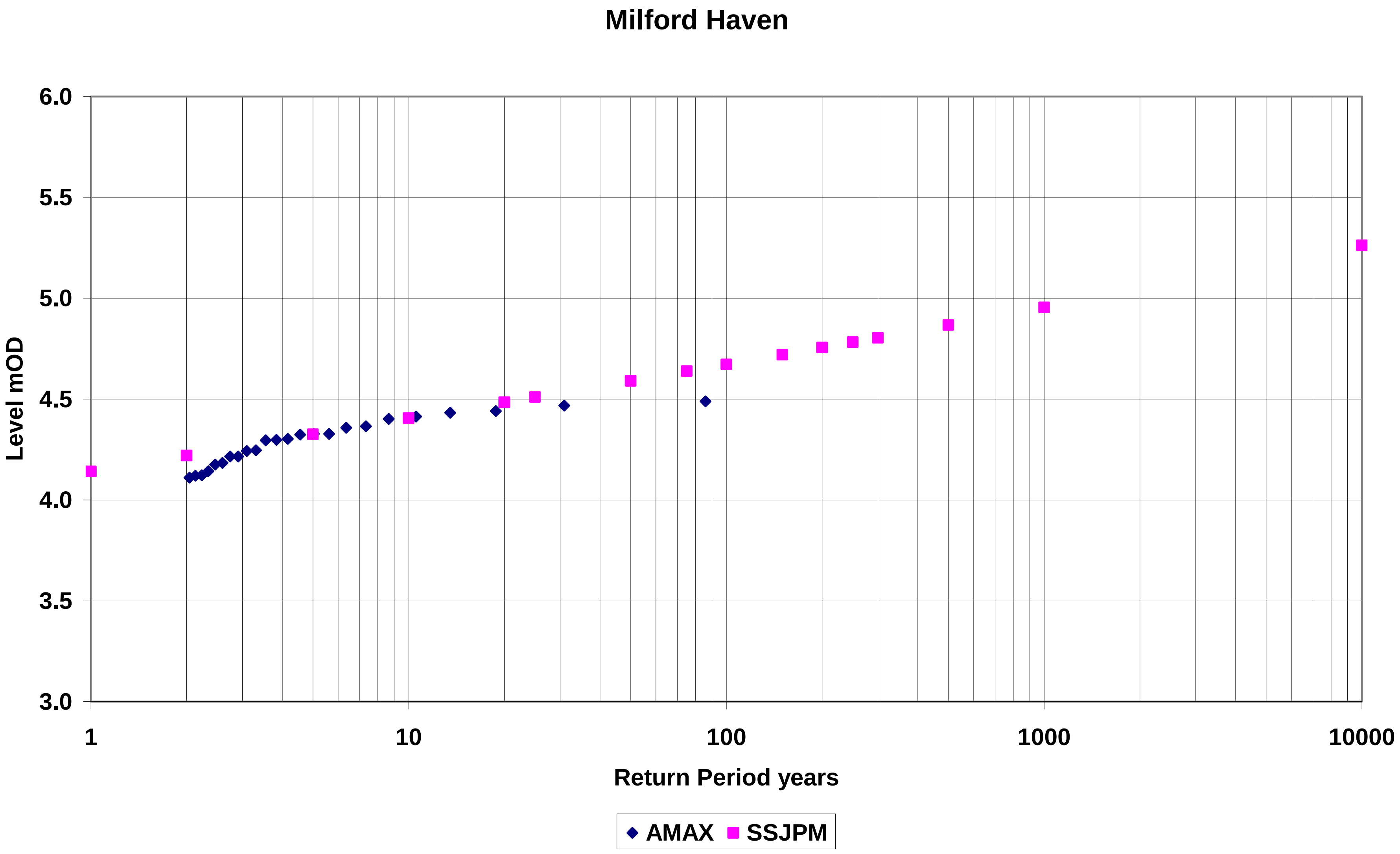

Hinkley Point
Level mOD
9.0
8.5
8.0
7.5
7.0
6.5
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM Smooth


Avonmouth
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Level mOD
1
10
100
1000
10000
Return Period years
SSJPM smooth
AMAX

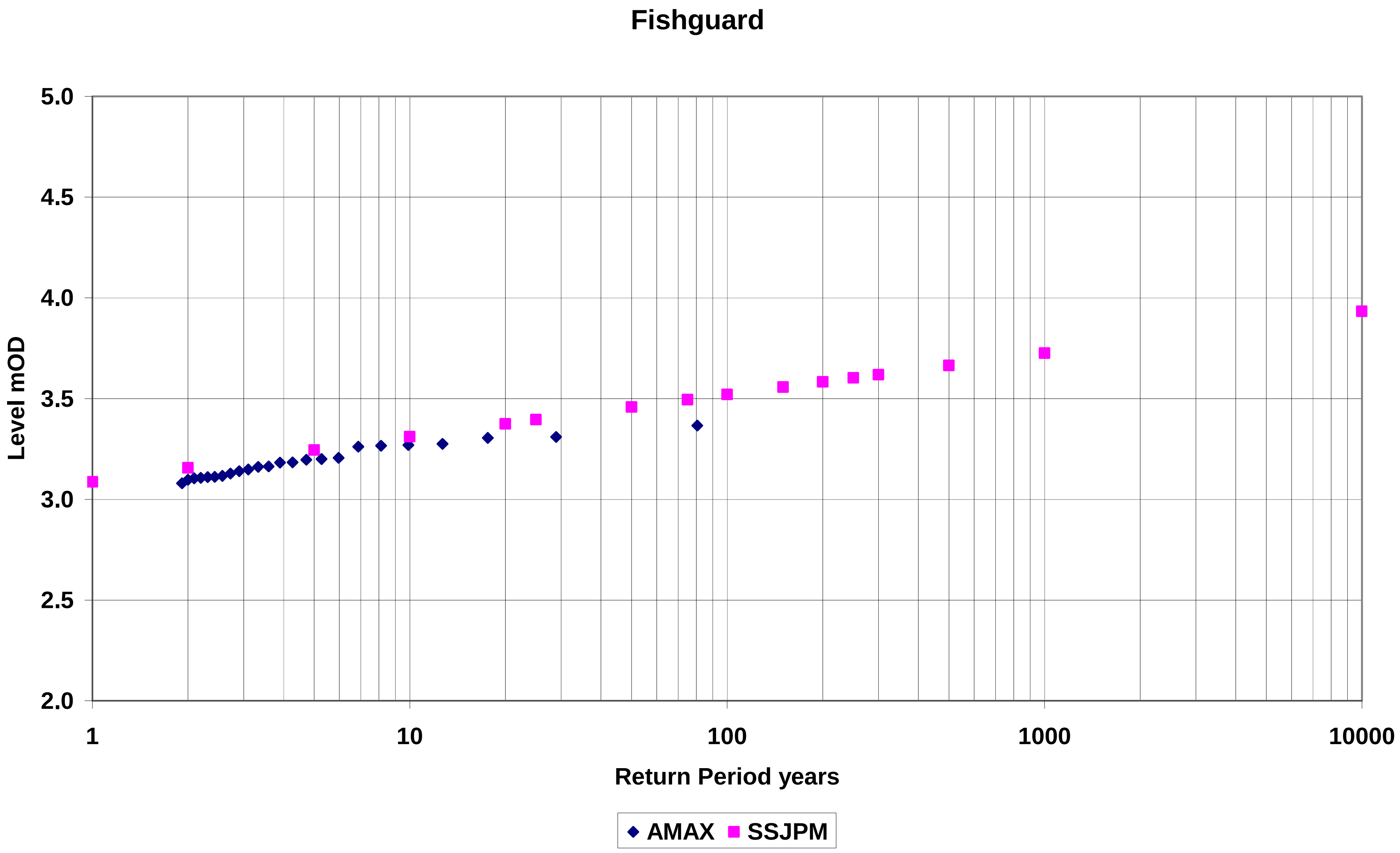

Newport
Level mOD
9.5
9.0
8.5
8.0
7.5
7.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM Smooth

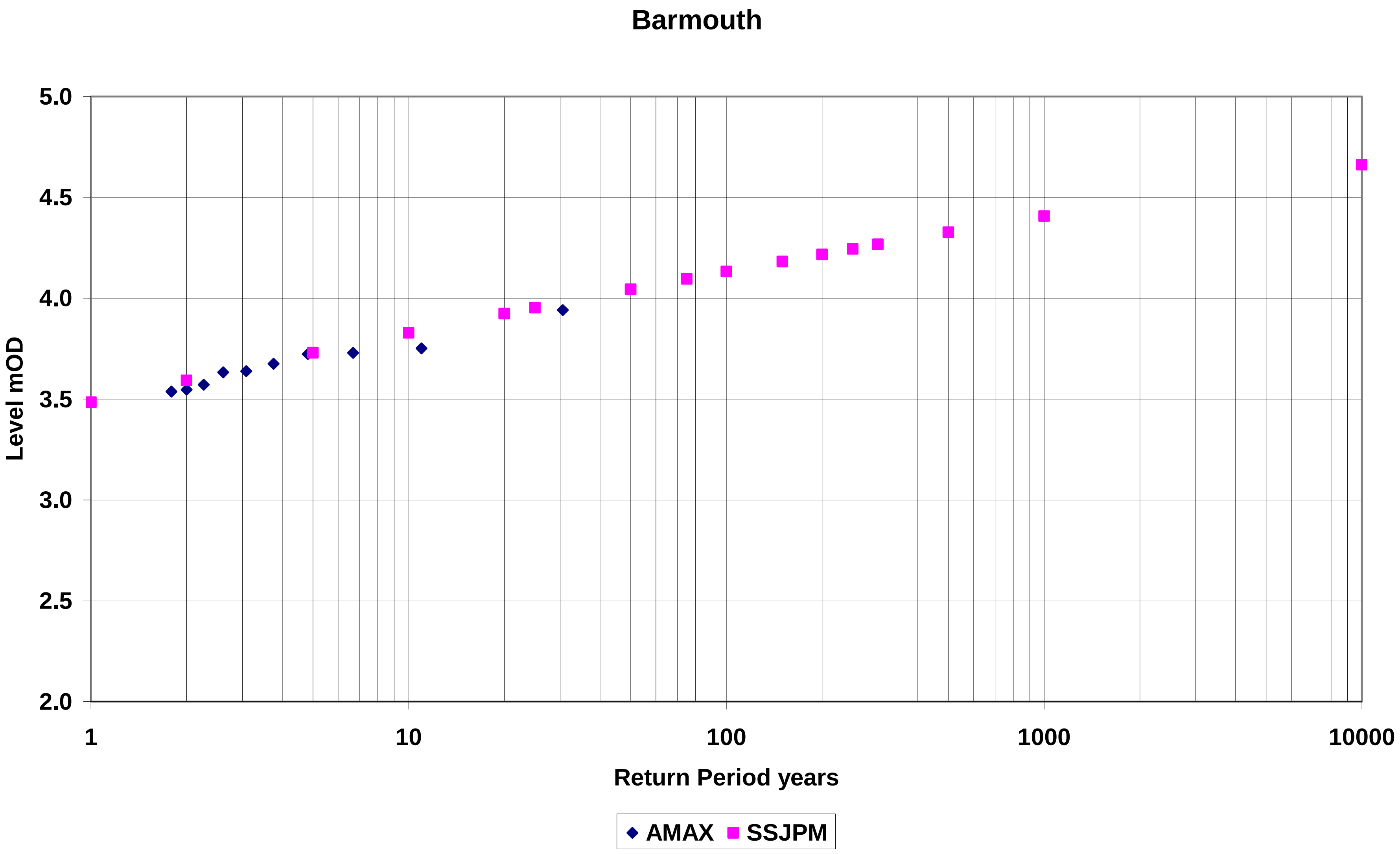
Mumbles

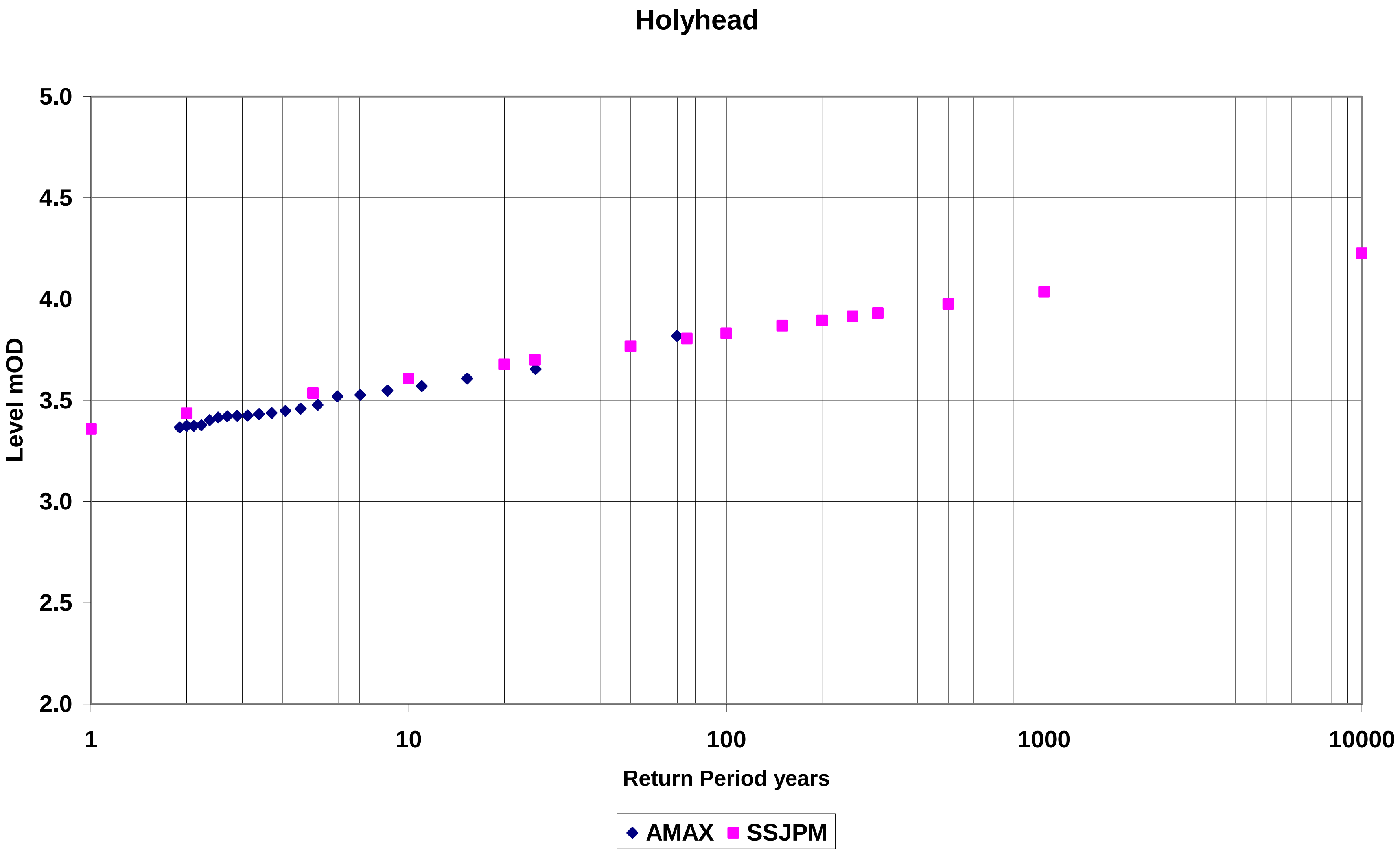

7.0
6.5
6.0
5.5
5.0
4.5
4.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

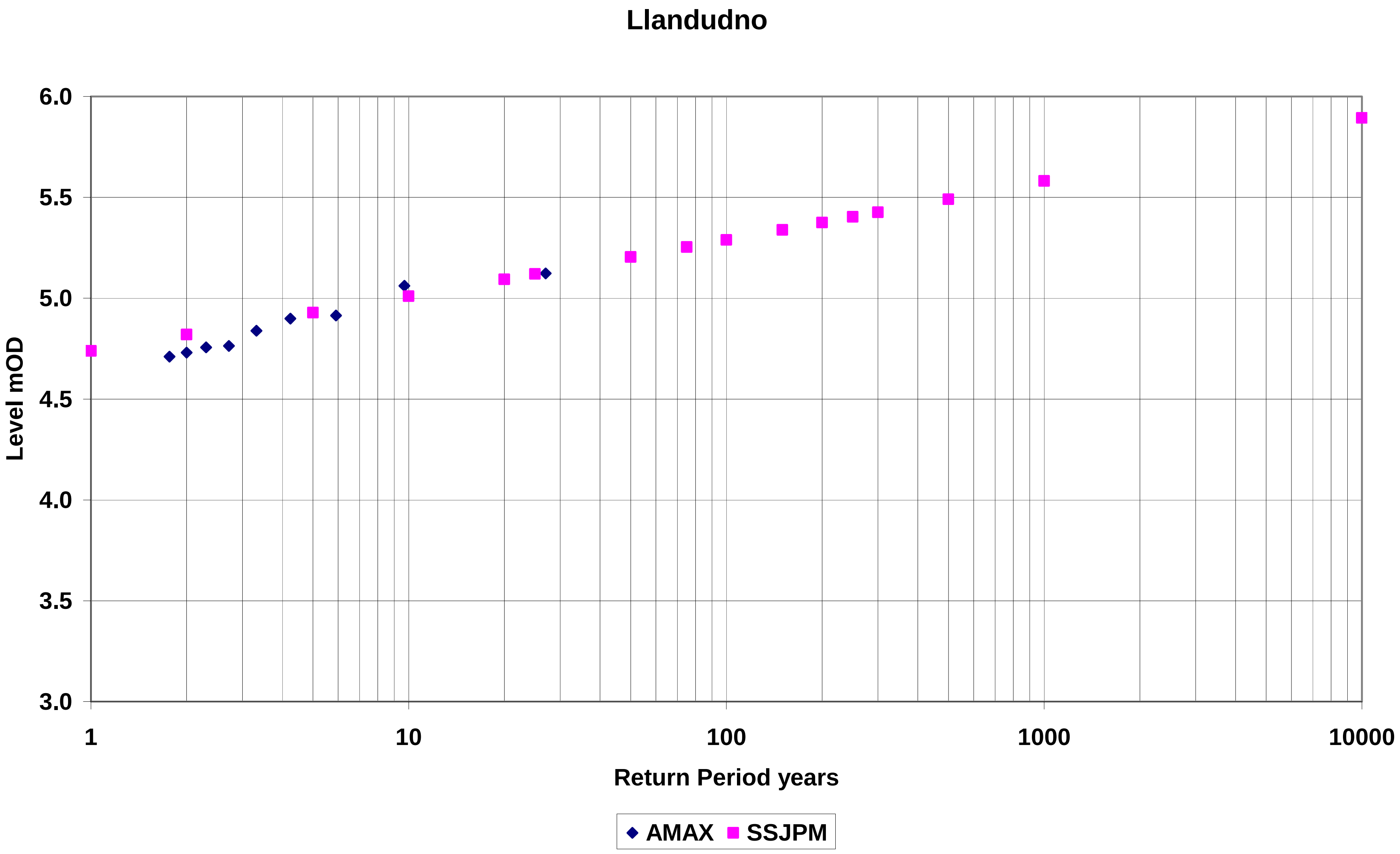


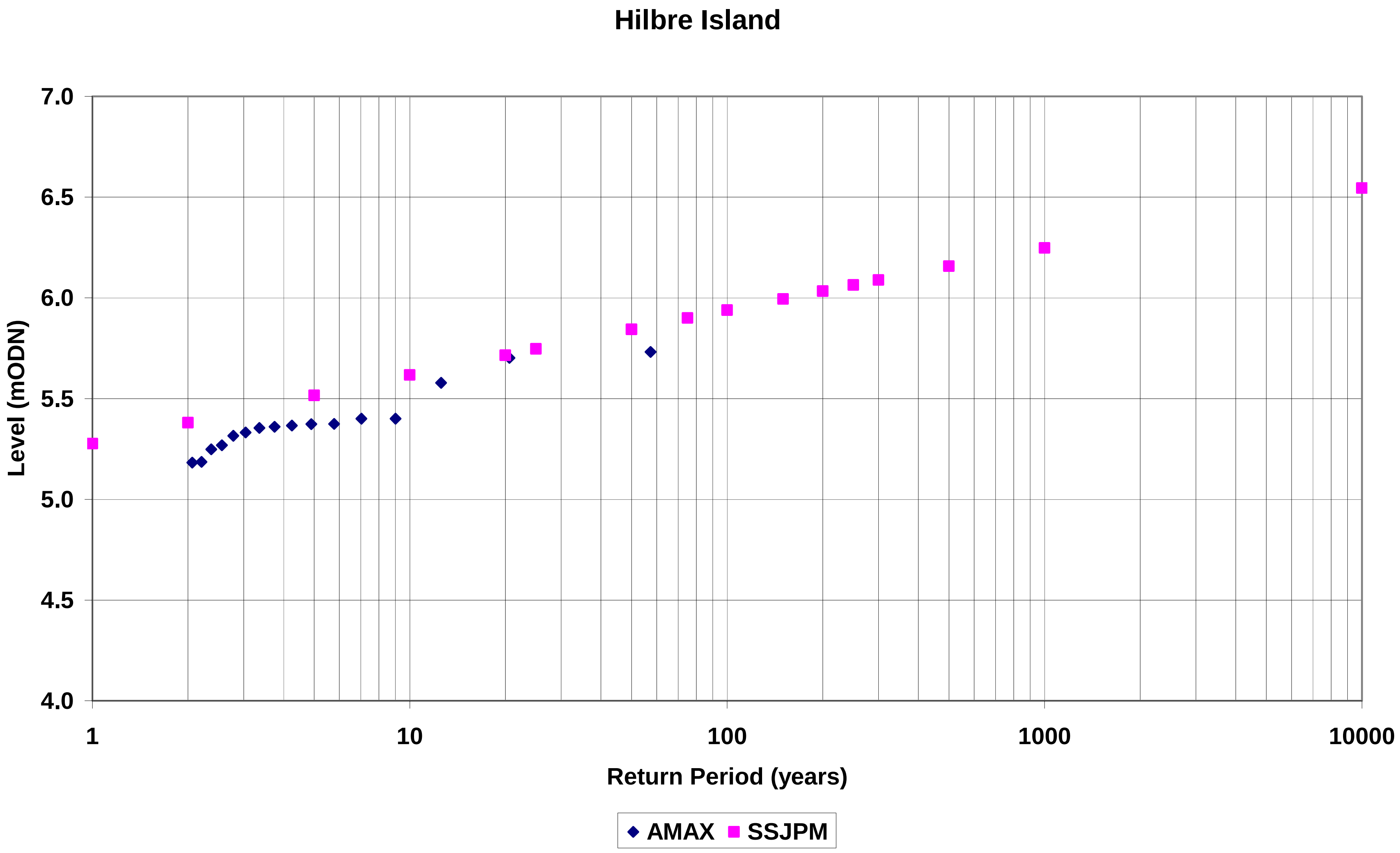
Milford Haven
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX ■ SSJPM

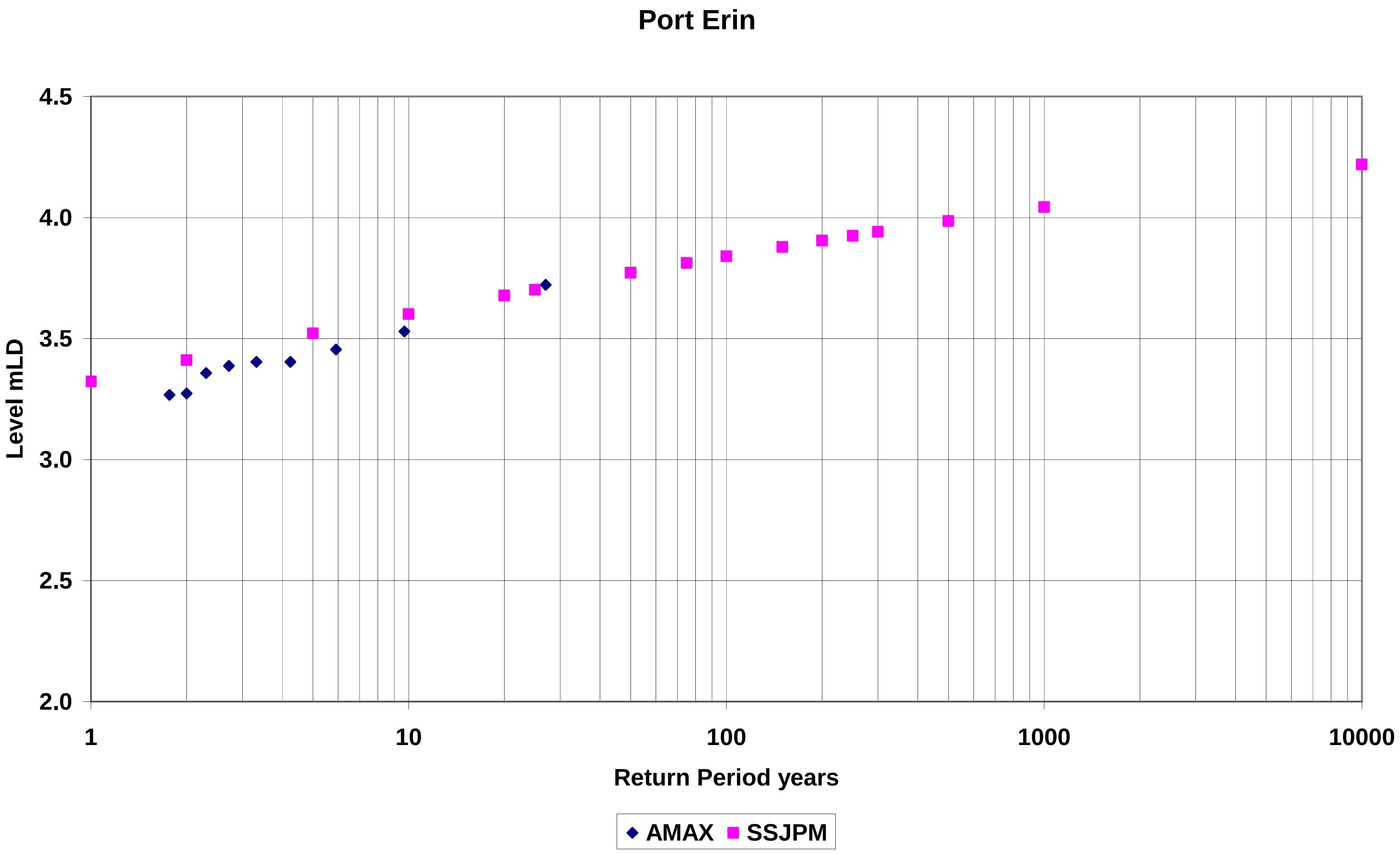

Fishguard
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

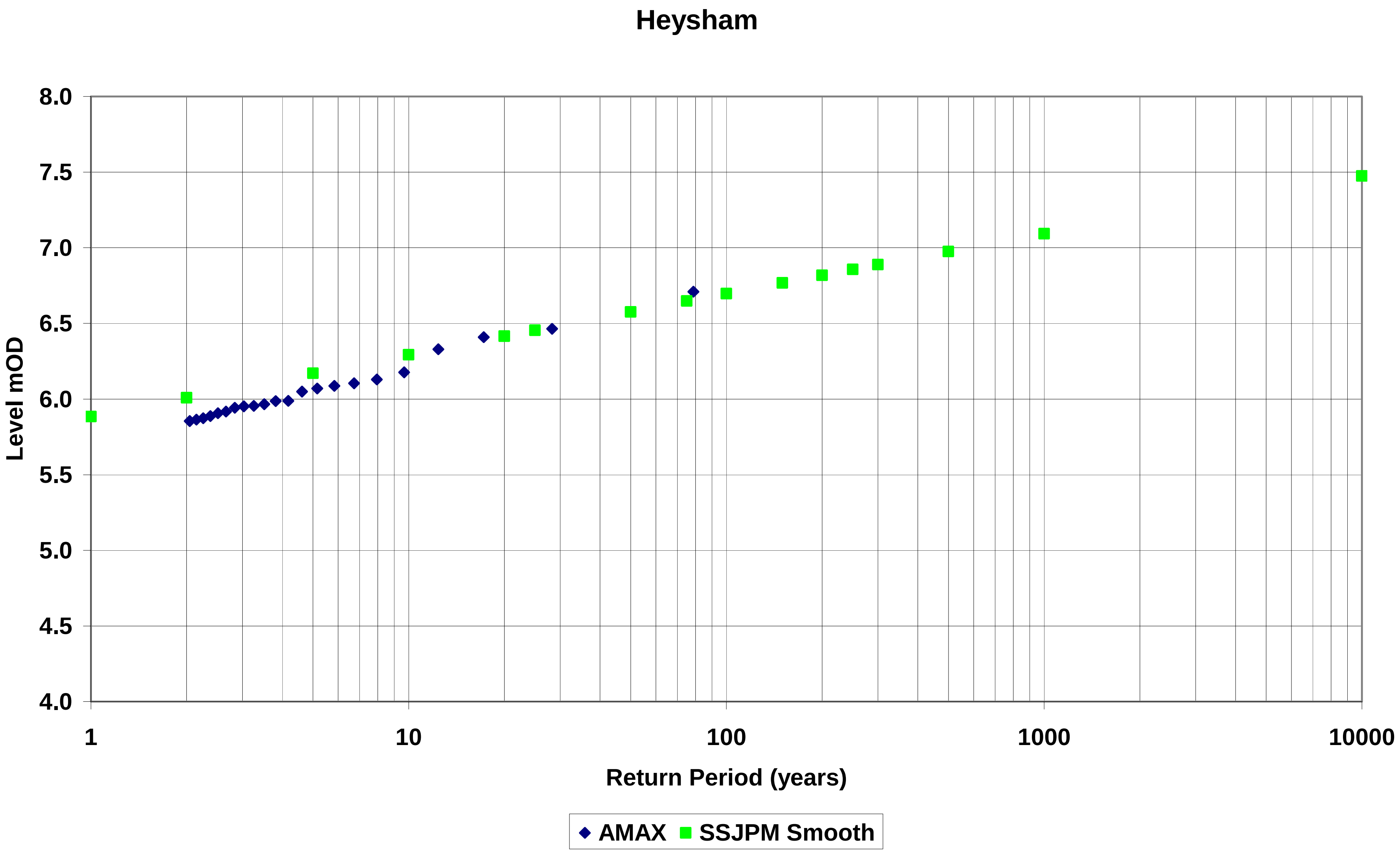

Barmouth
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

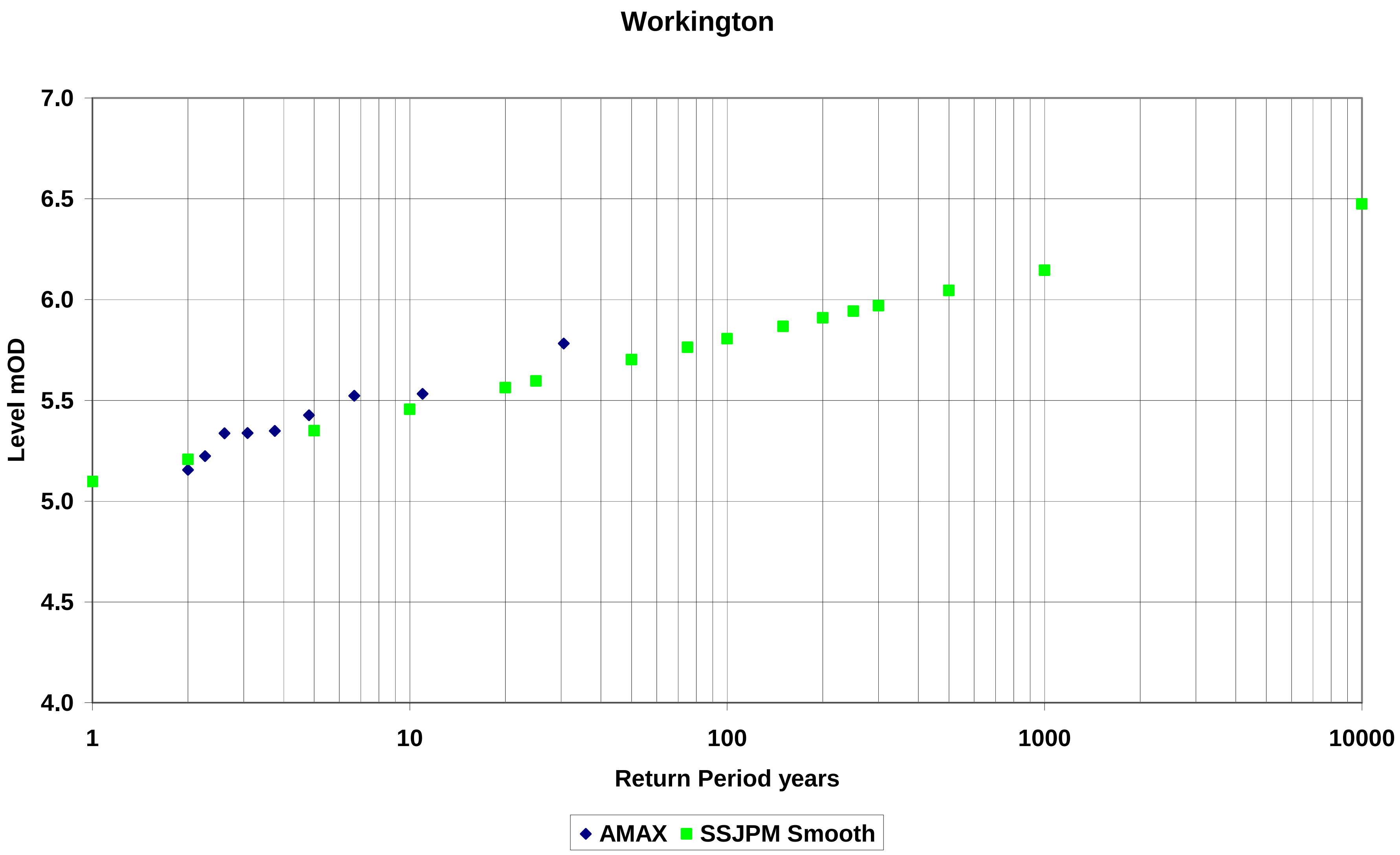

Holyhead
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

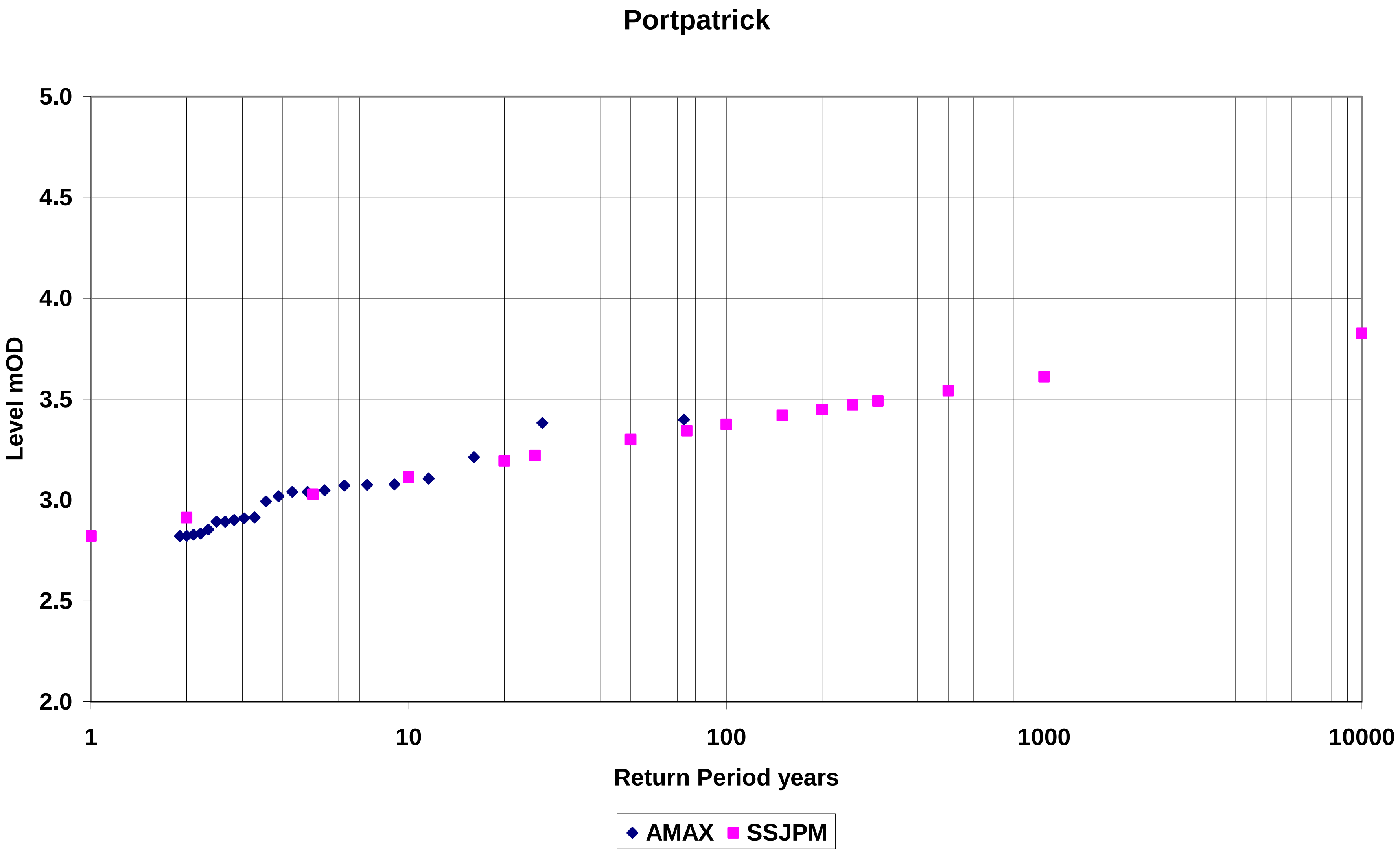

Llandudno
Level mOD
6.0
5.5
5.0
4.5
4.0
3.5
3.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

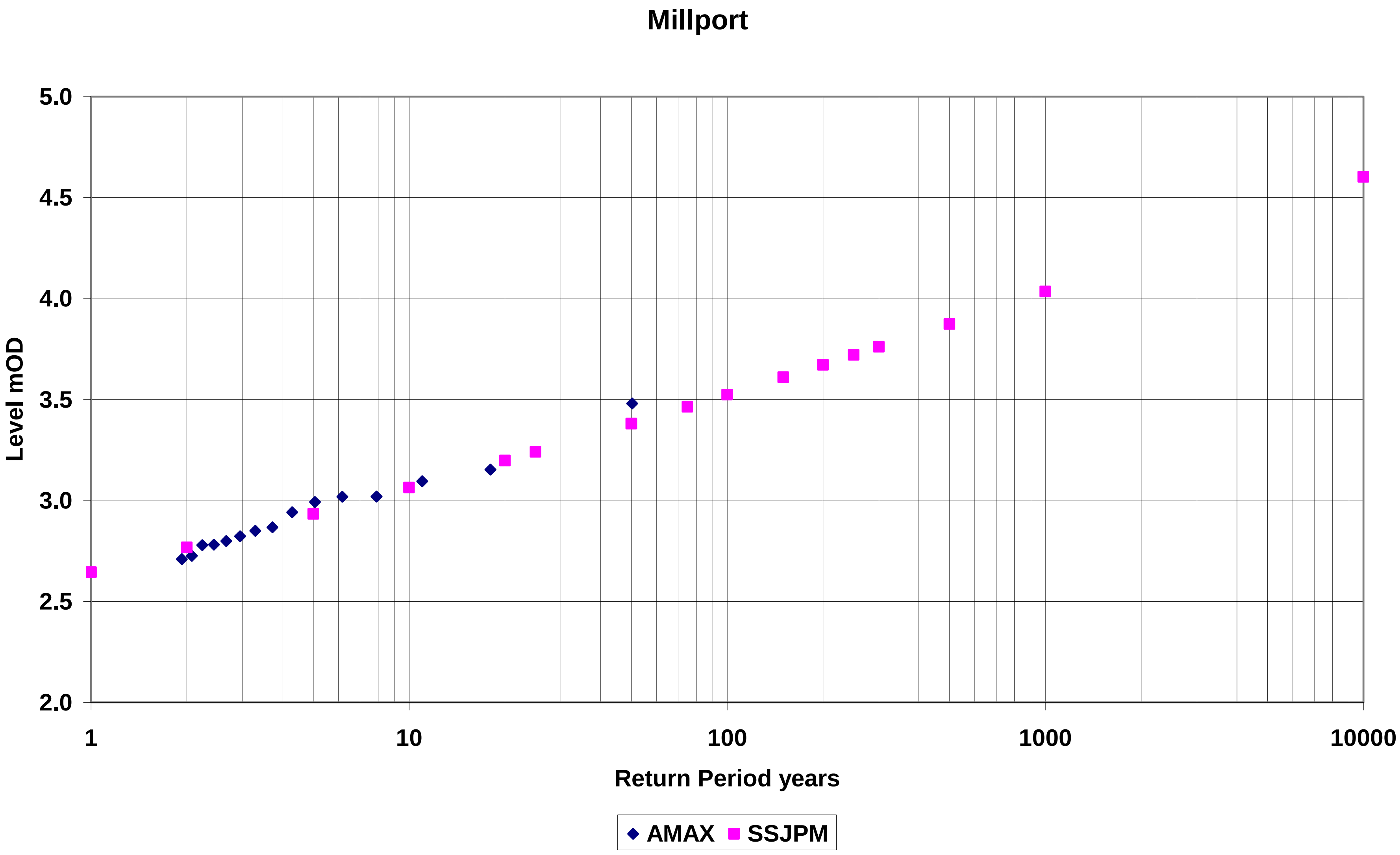

Hilbre Island
7.0
6.5
6.0
5.5
5.0
4.5
4.0
Level (mODN)
1
10
100
1000
10000
Return Period (years)
◆ AMAX
■ SSJPM

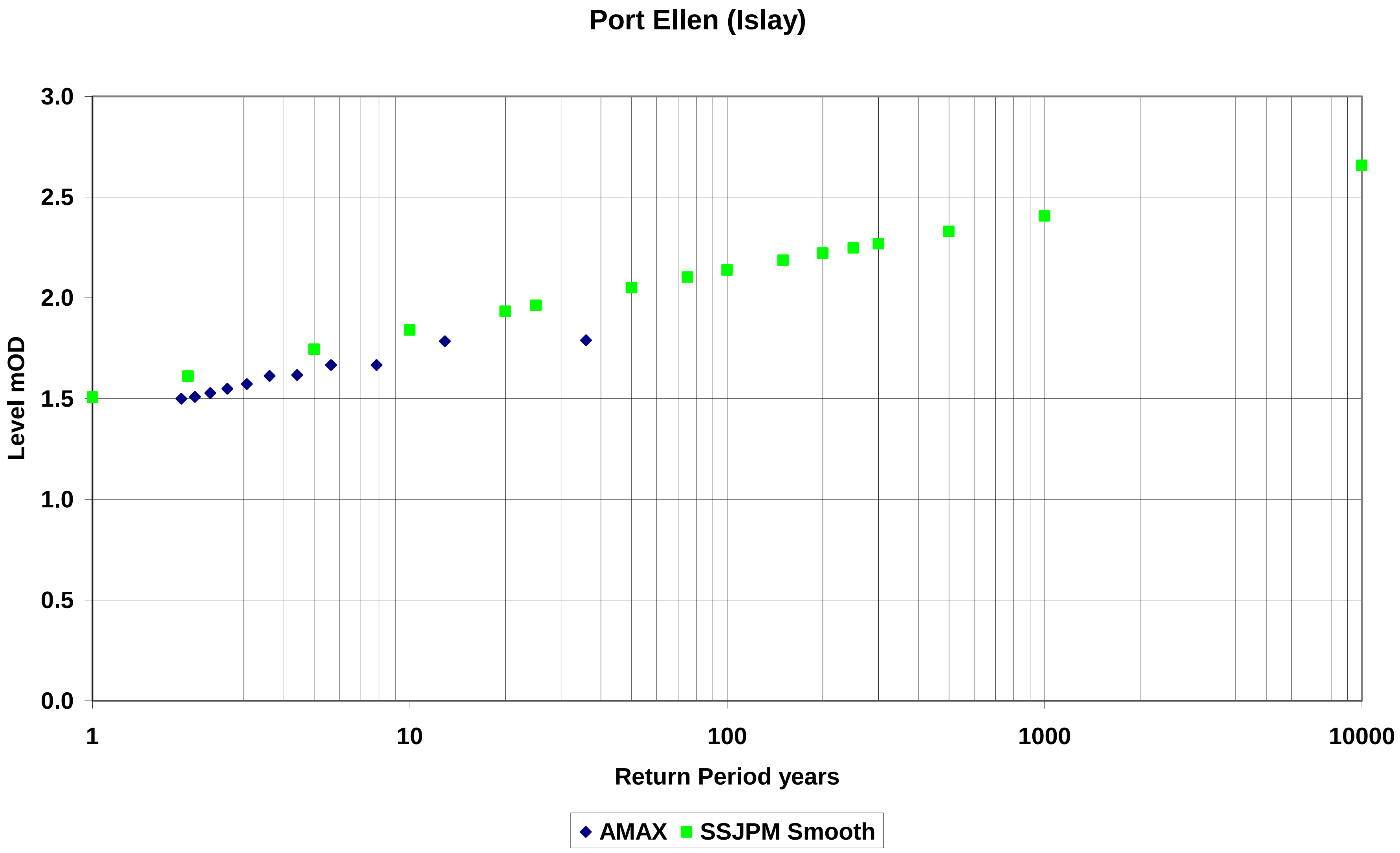

Port Erin
Level mLD
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

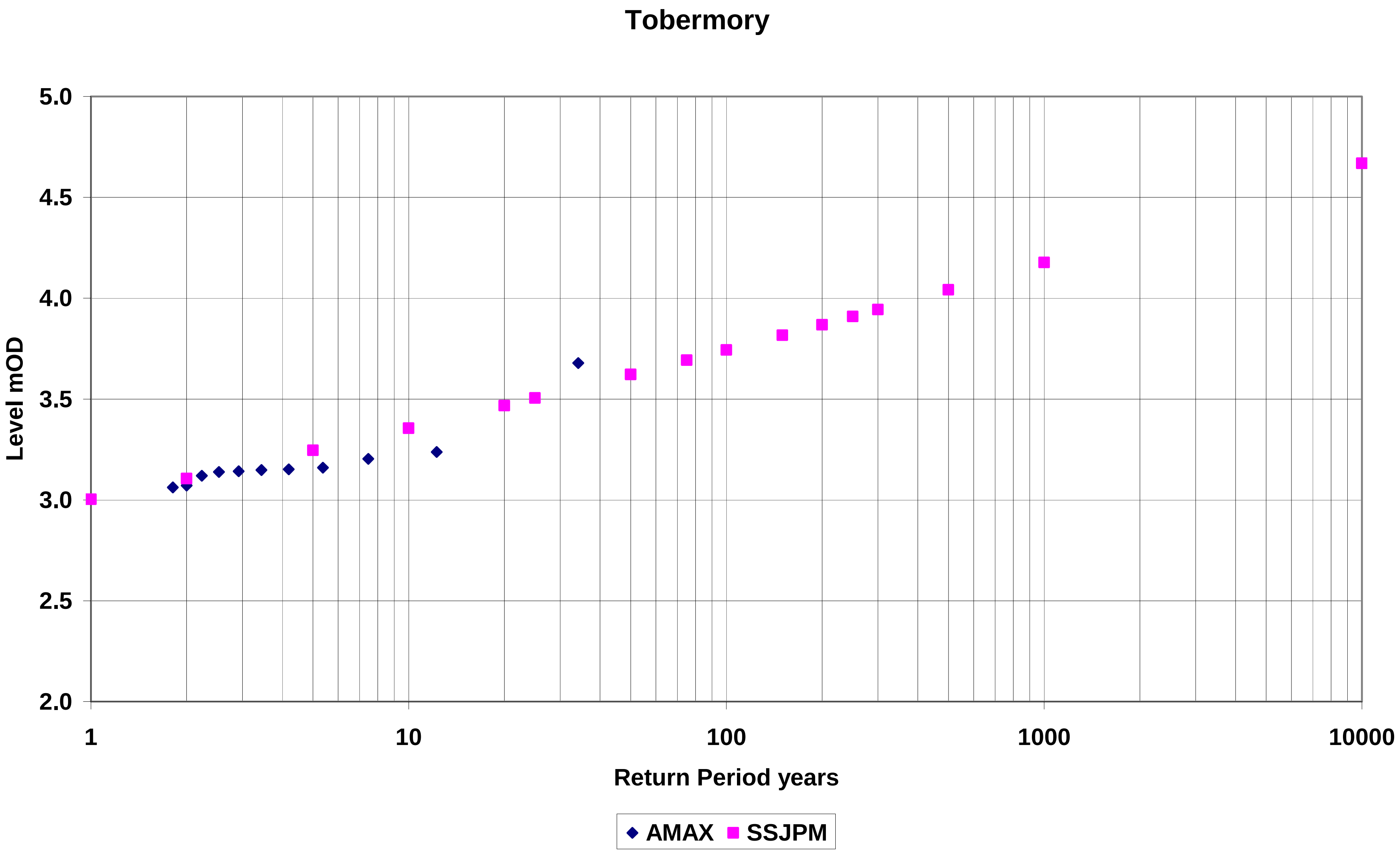

Heysham
Level mOD
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
1
10
100
1000
10000
Return Period (years)
◆ AMAX
🟩 SSJPM Smooth

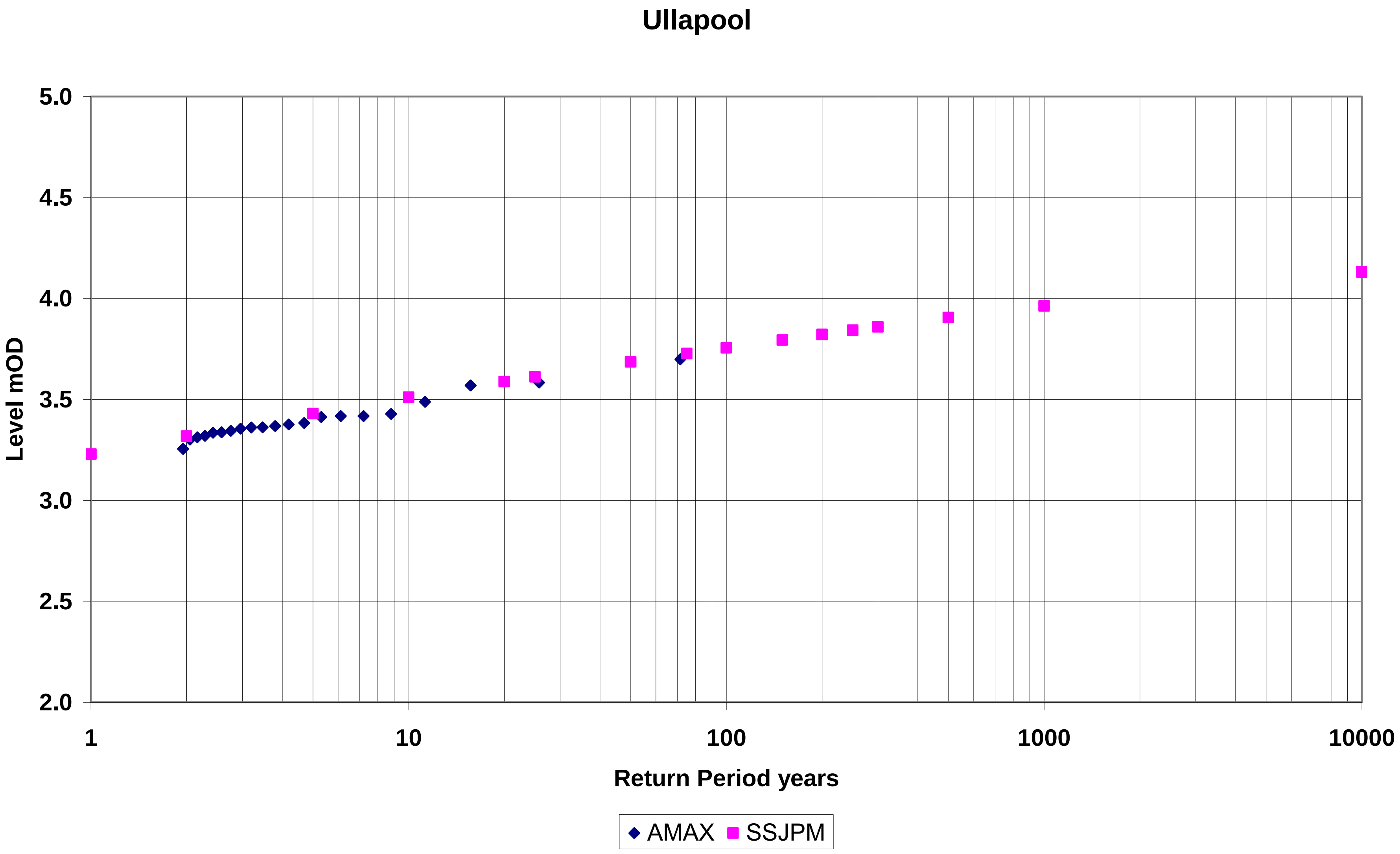

Workington
Level mOD
7.0
6.5
6.0
5.5
5.0
4.5
4.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM Smooth

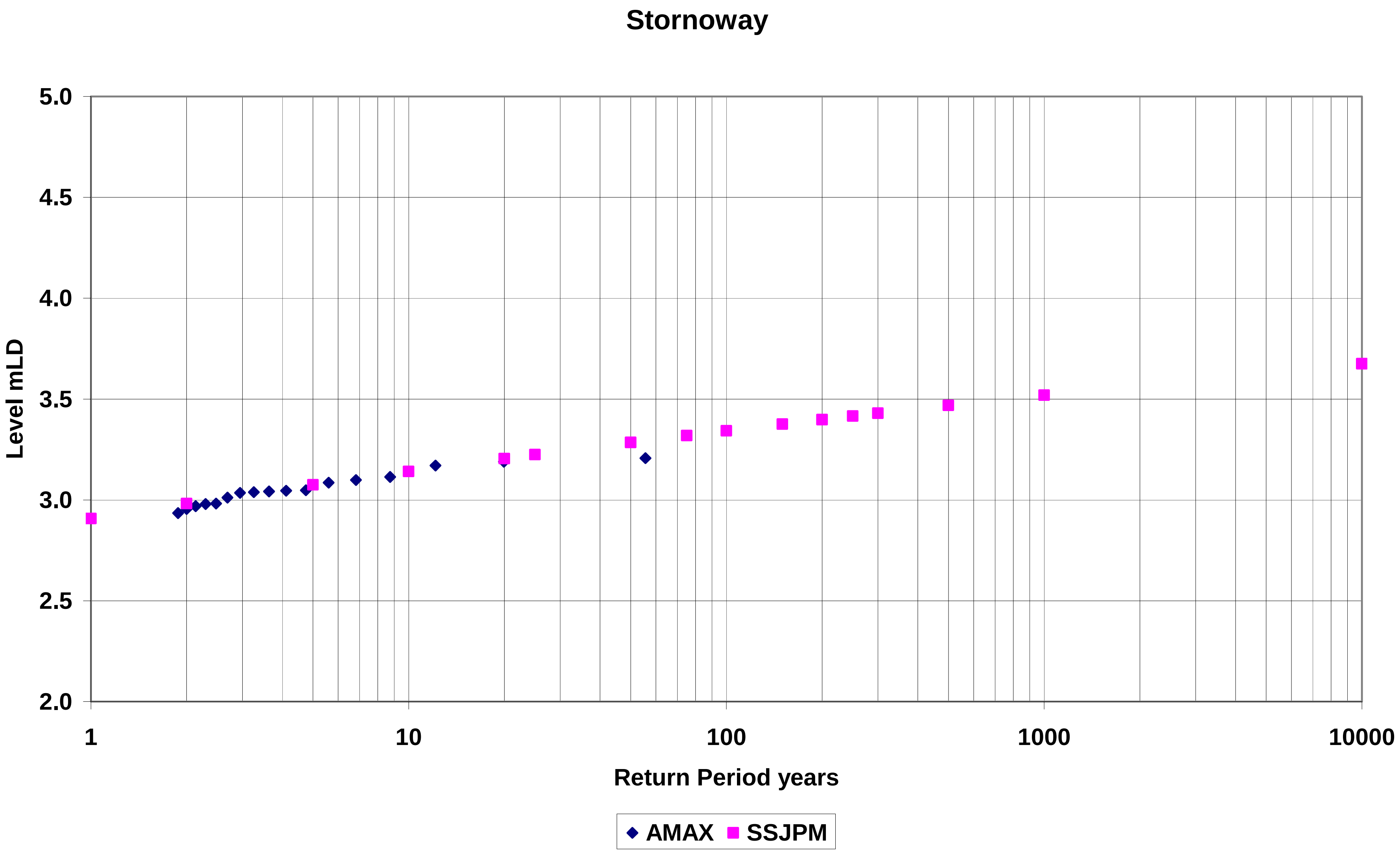

Portpatrick
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

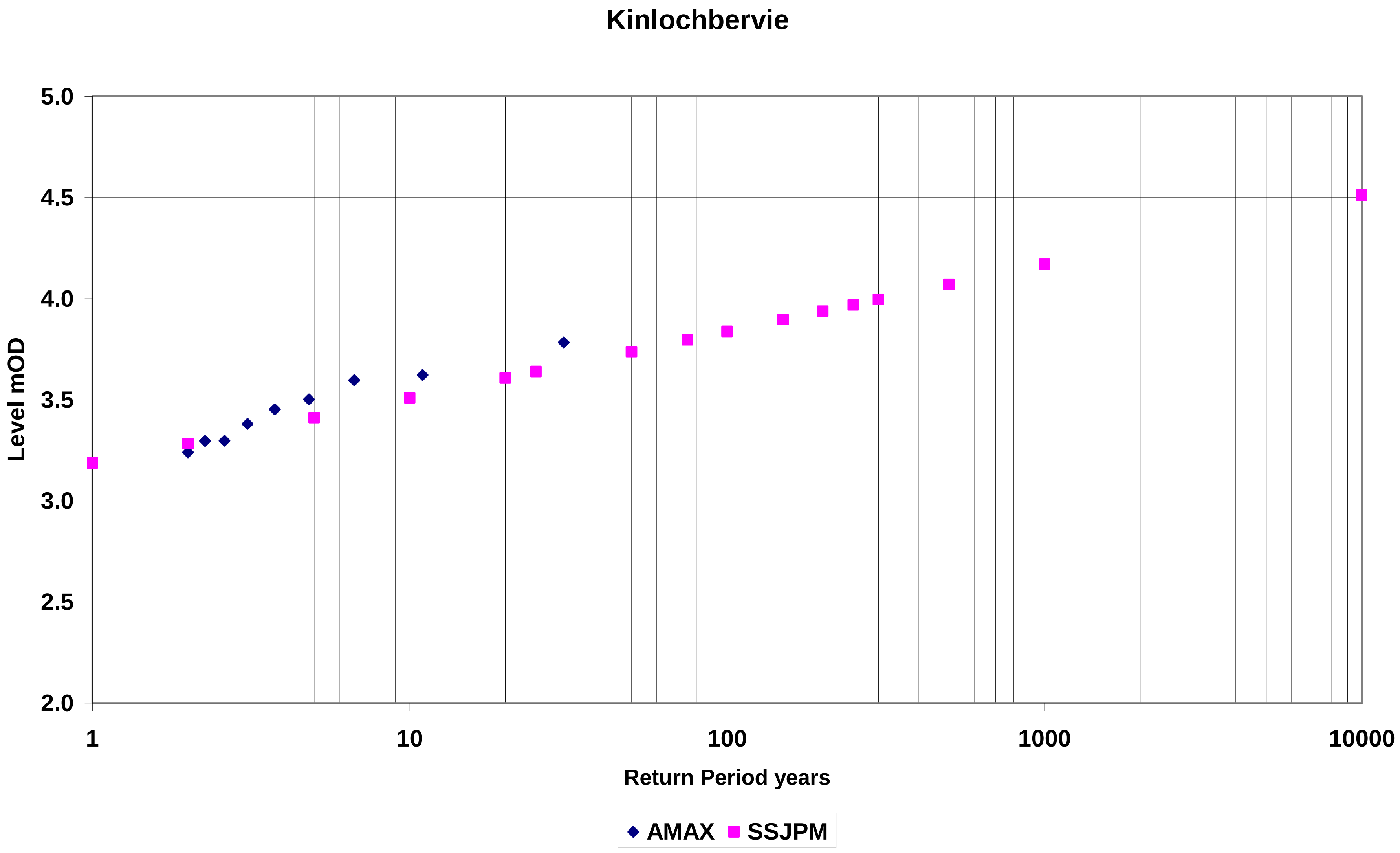

Millport
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

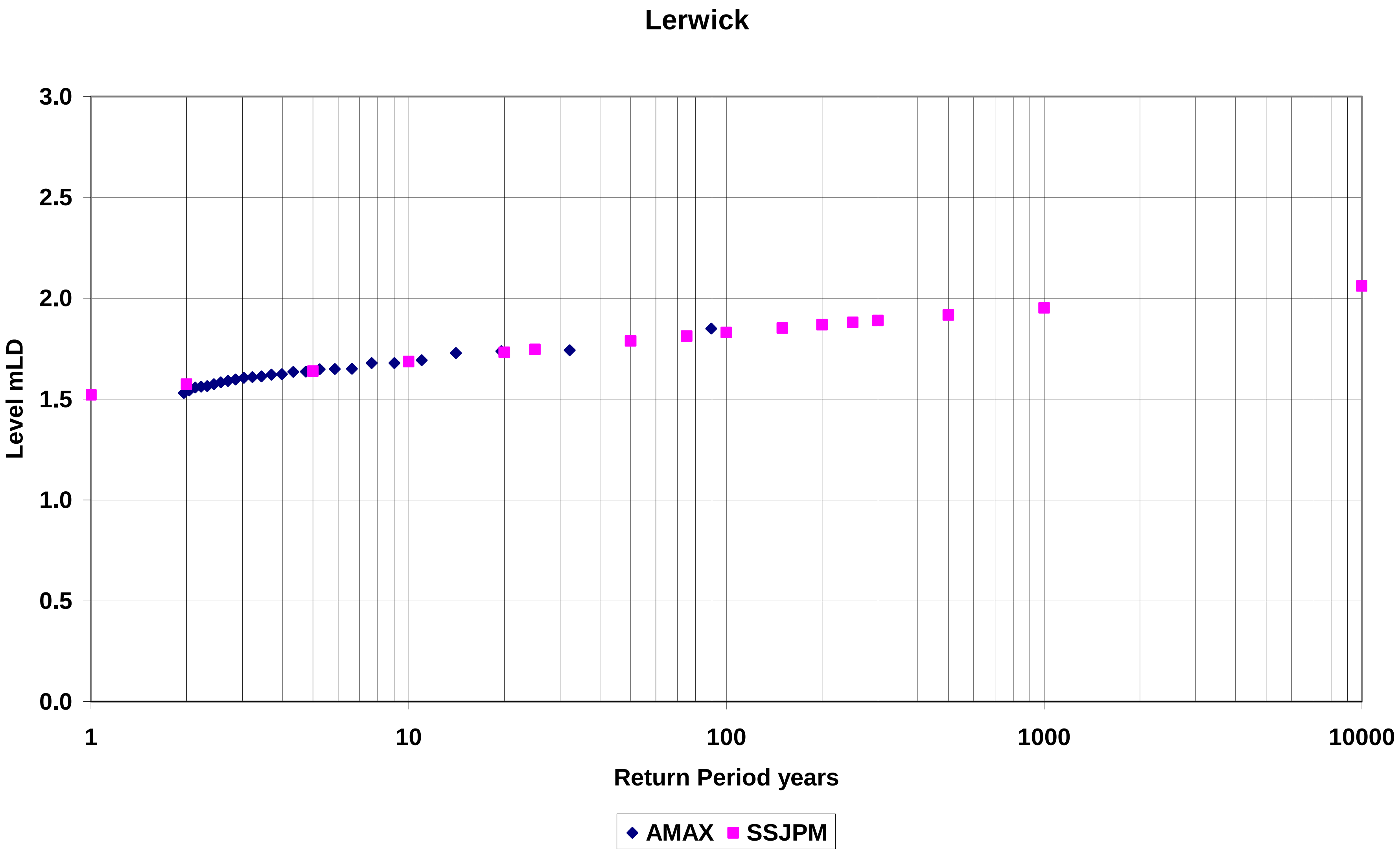

Port Ellen (Islay)
Level mOD
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM Smooth

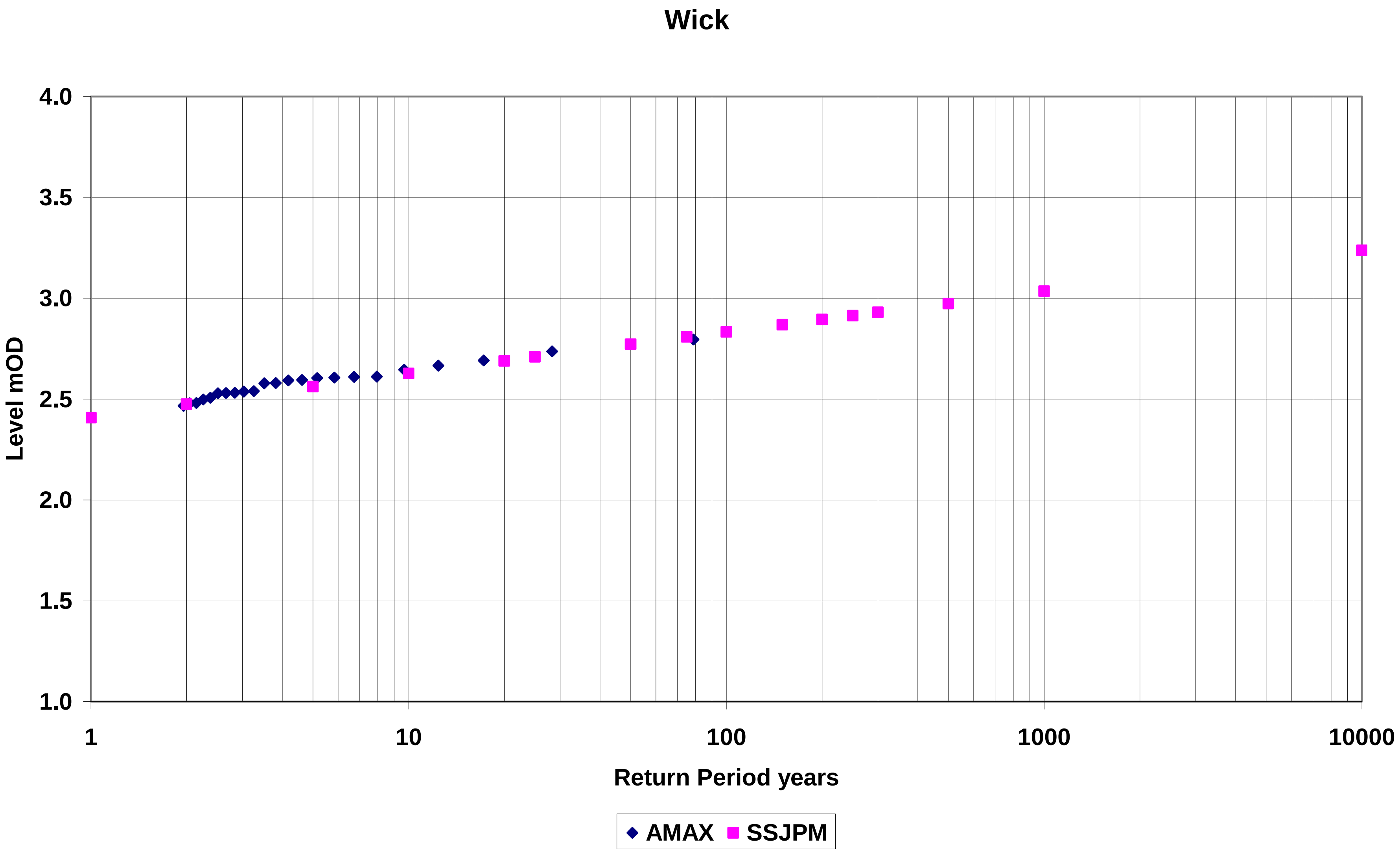

Tobermory
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

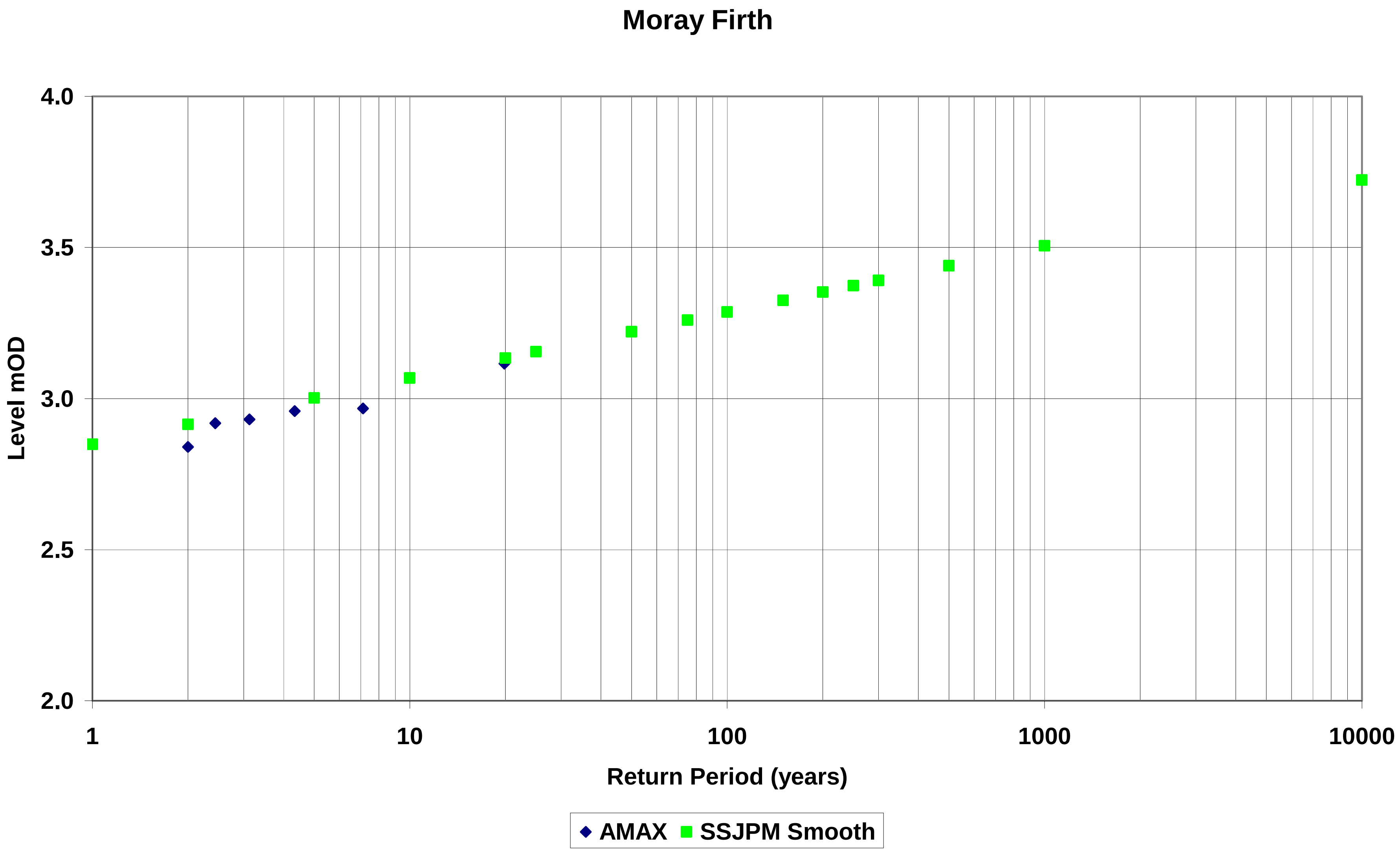

Ullapool
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

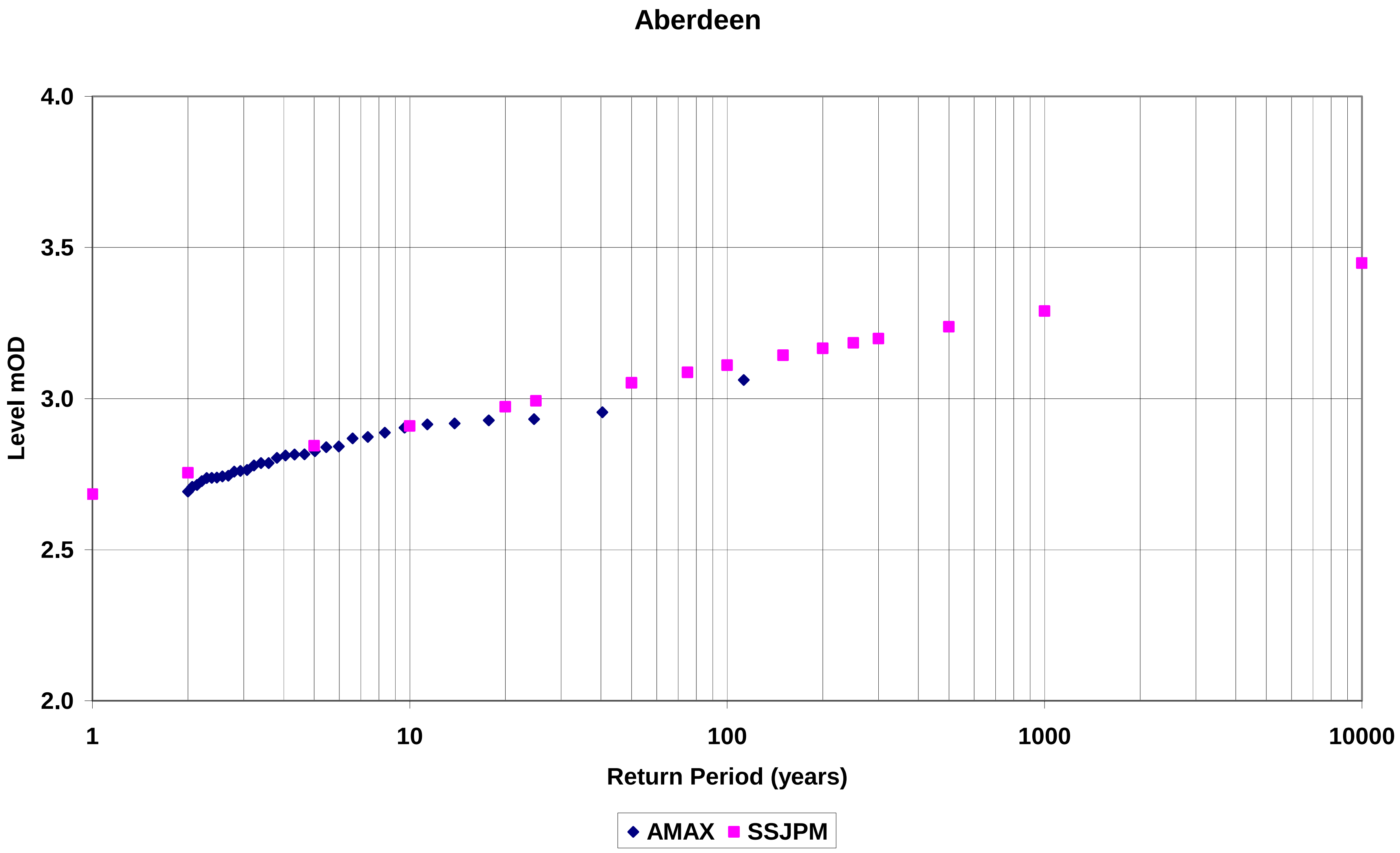

Stornoway
Level mLD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

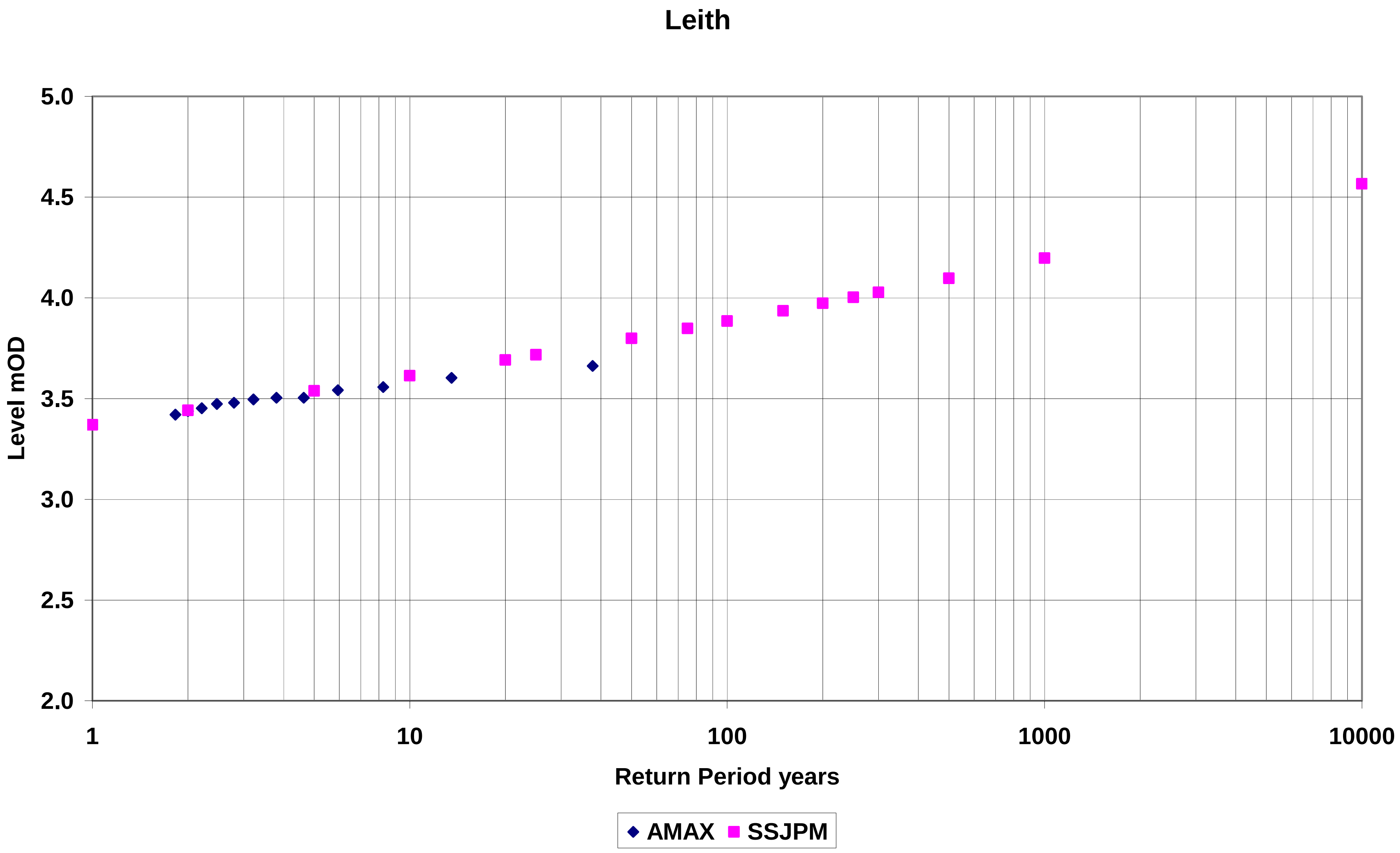

Kinlochbervie
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

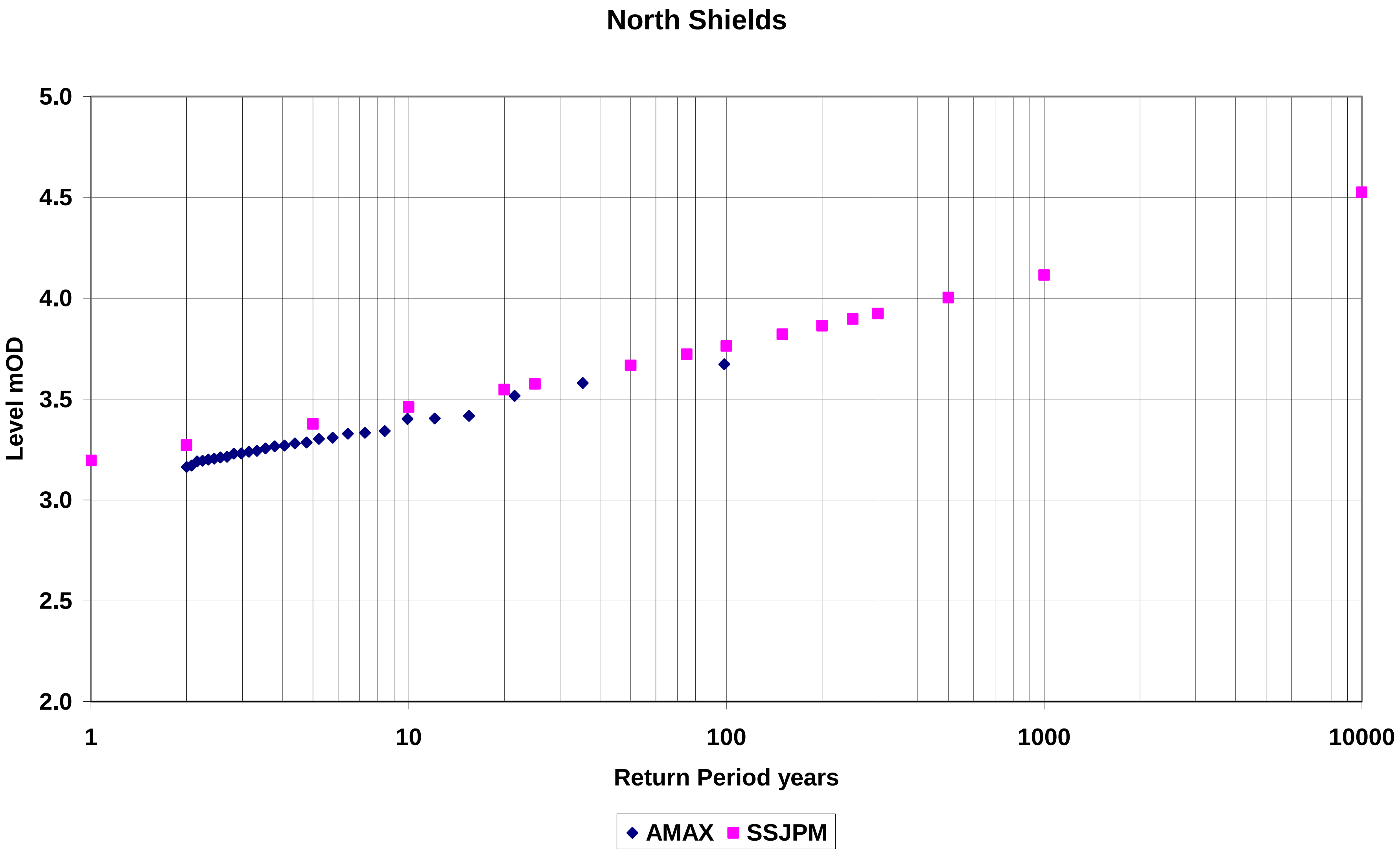

Lerwick
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Level mLD
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

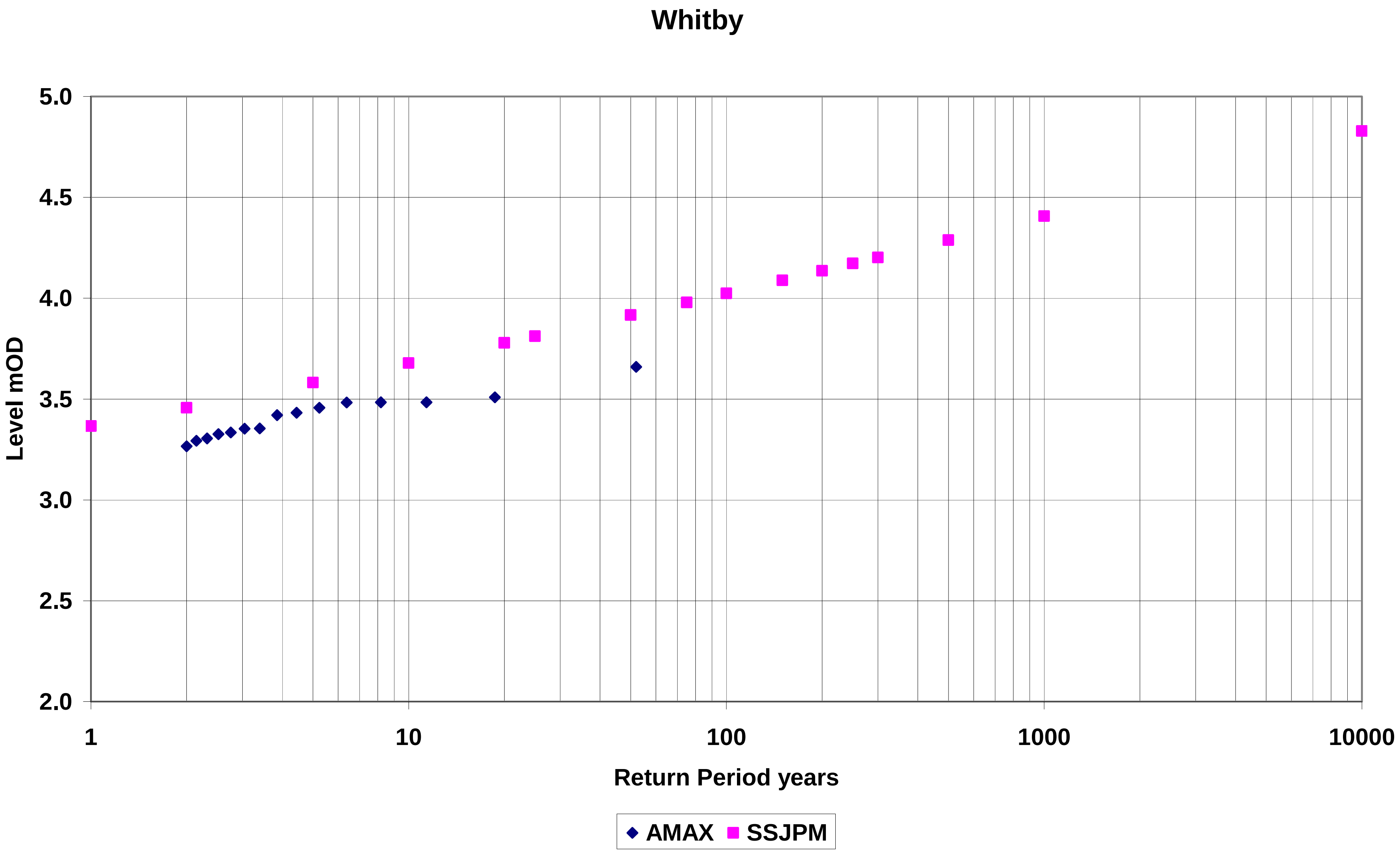

Wick
4.0
3.5
3.0
2.5
2.0
1.5
1.0
Level mOD
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

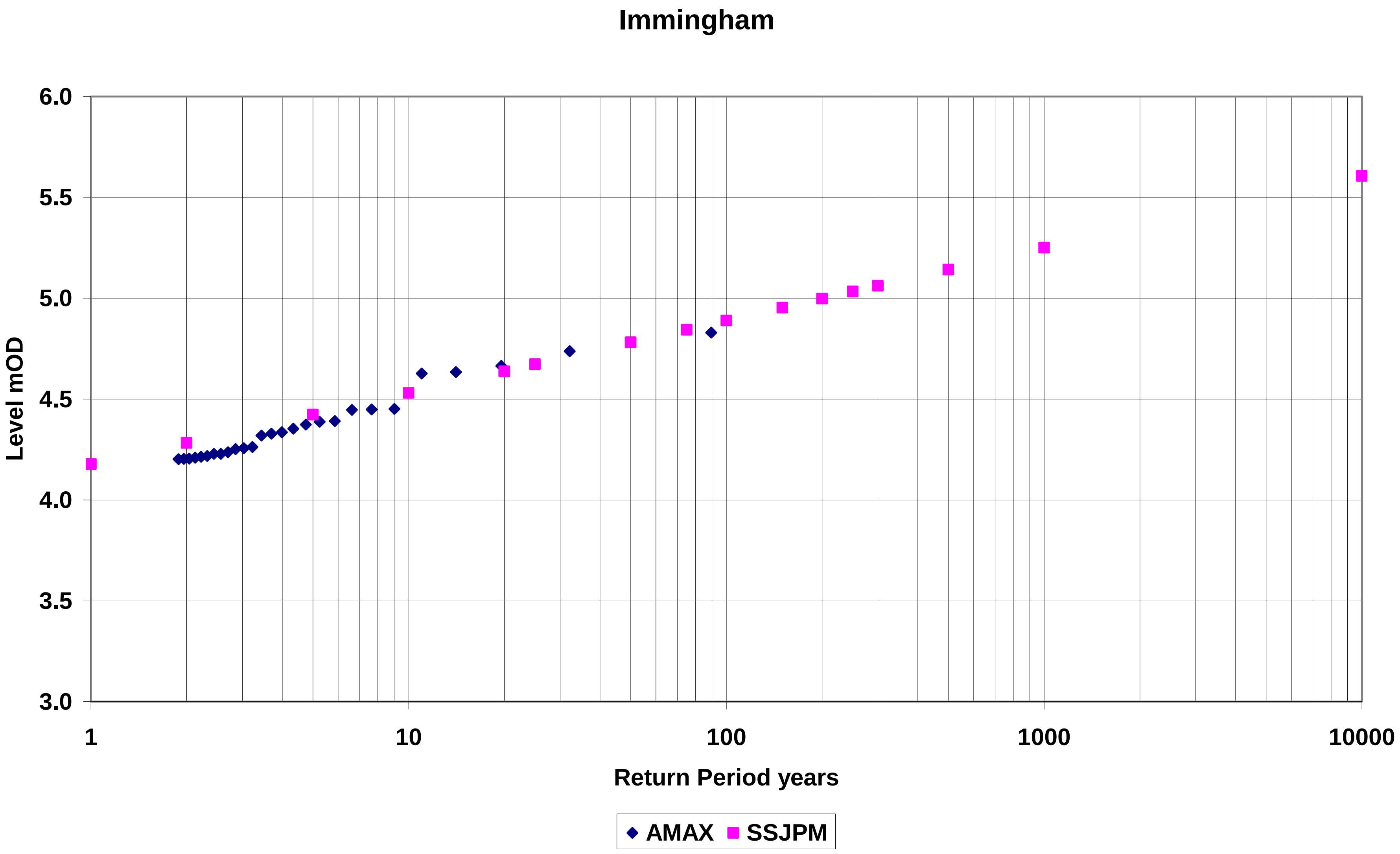

Moray Firth
Level mOD
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period (years)
◆ AMAX
■ SSJPM Smooth

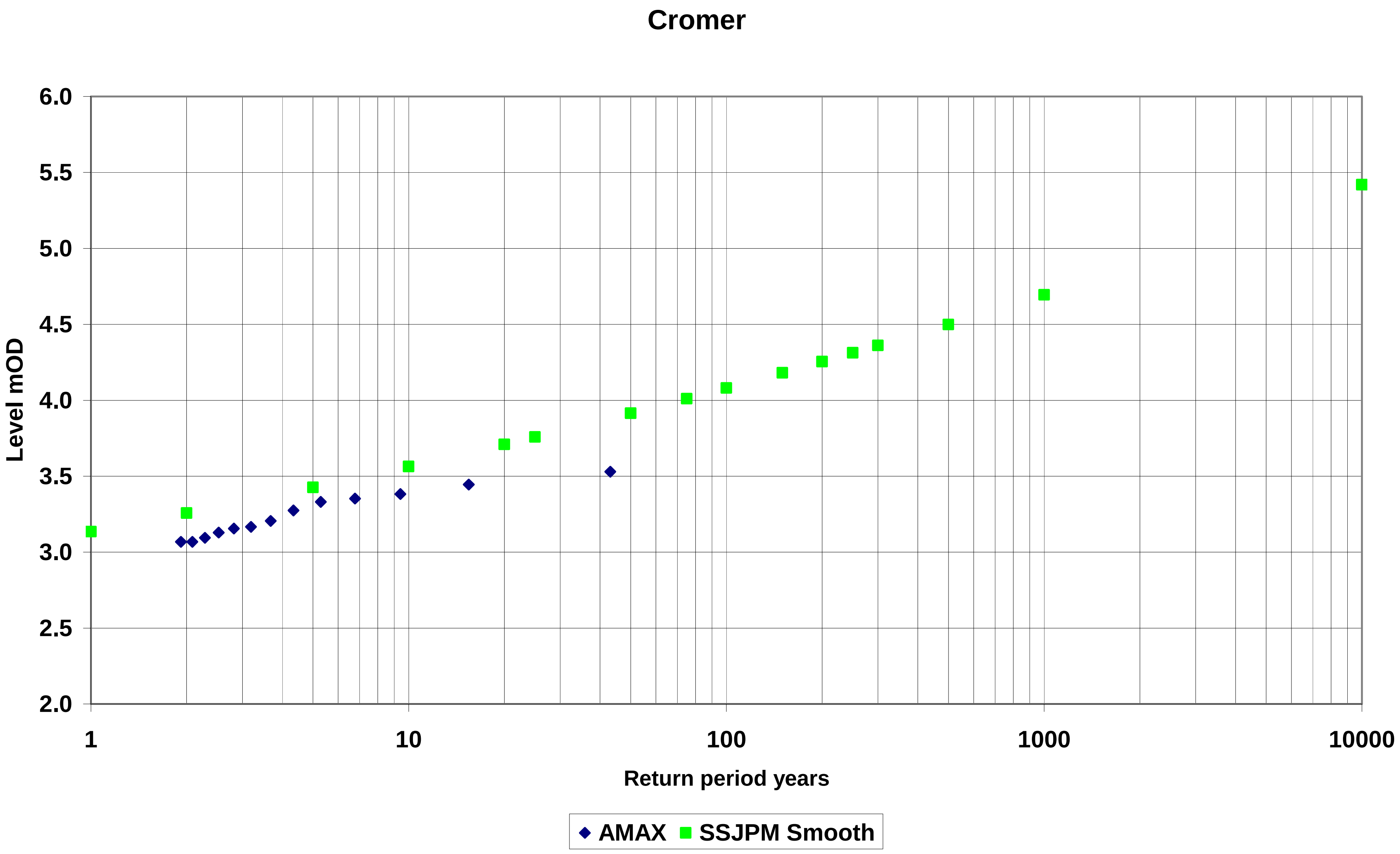

Aberdeen
Level mOD
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period (years)
◆ AMAX
■ SSJPM

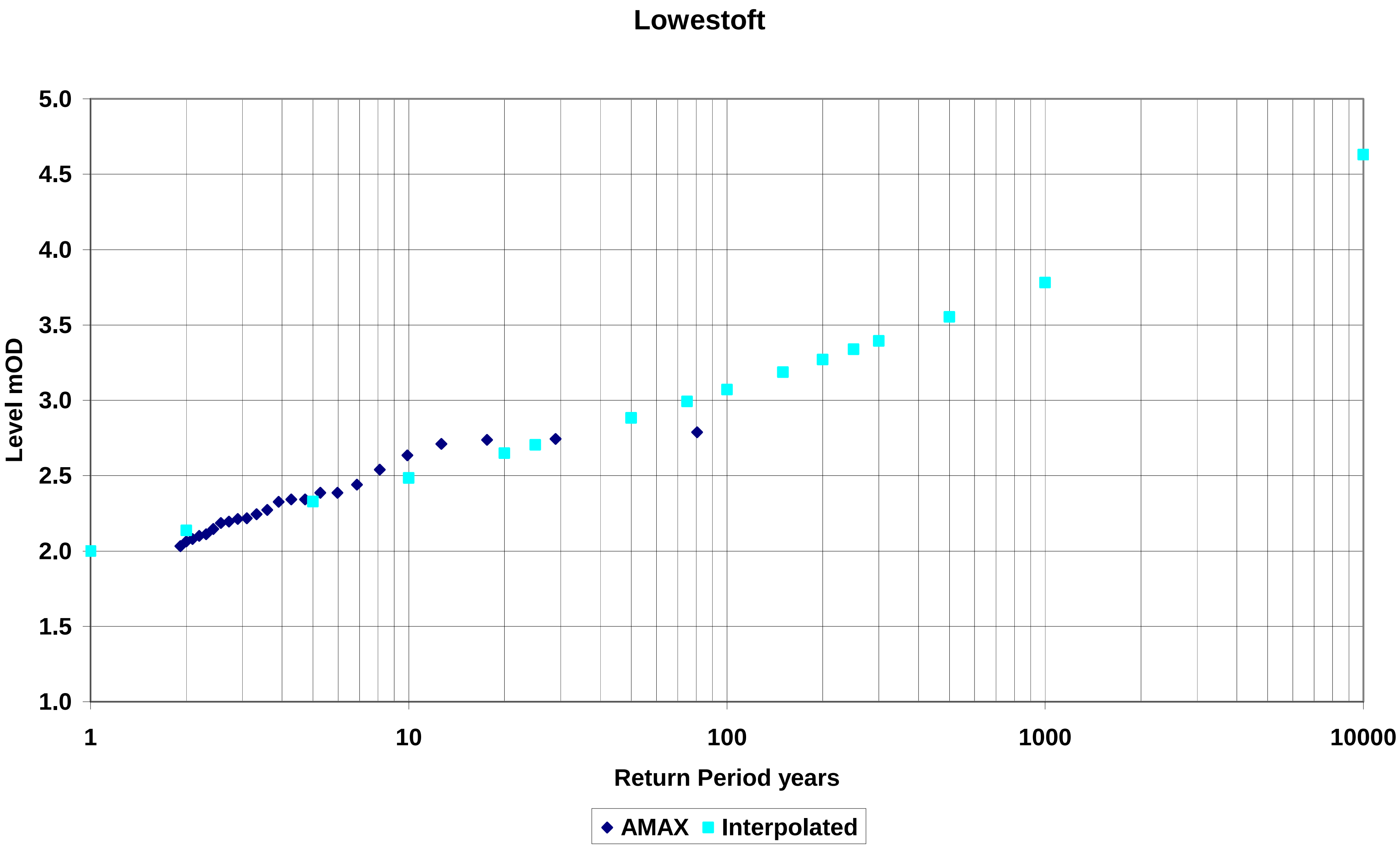

Leith
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Level mOD
1
10
100
1000
10000
Return Period years
AMAX
SSJPM

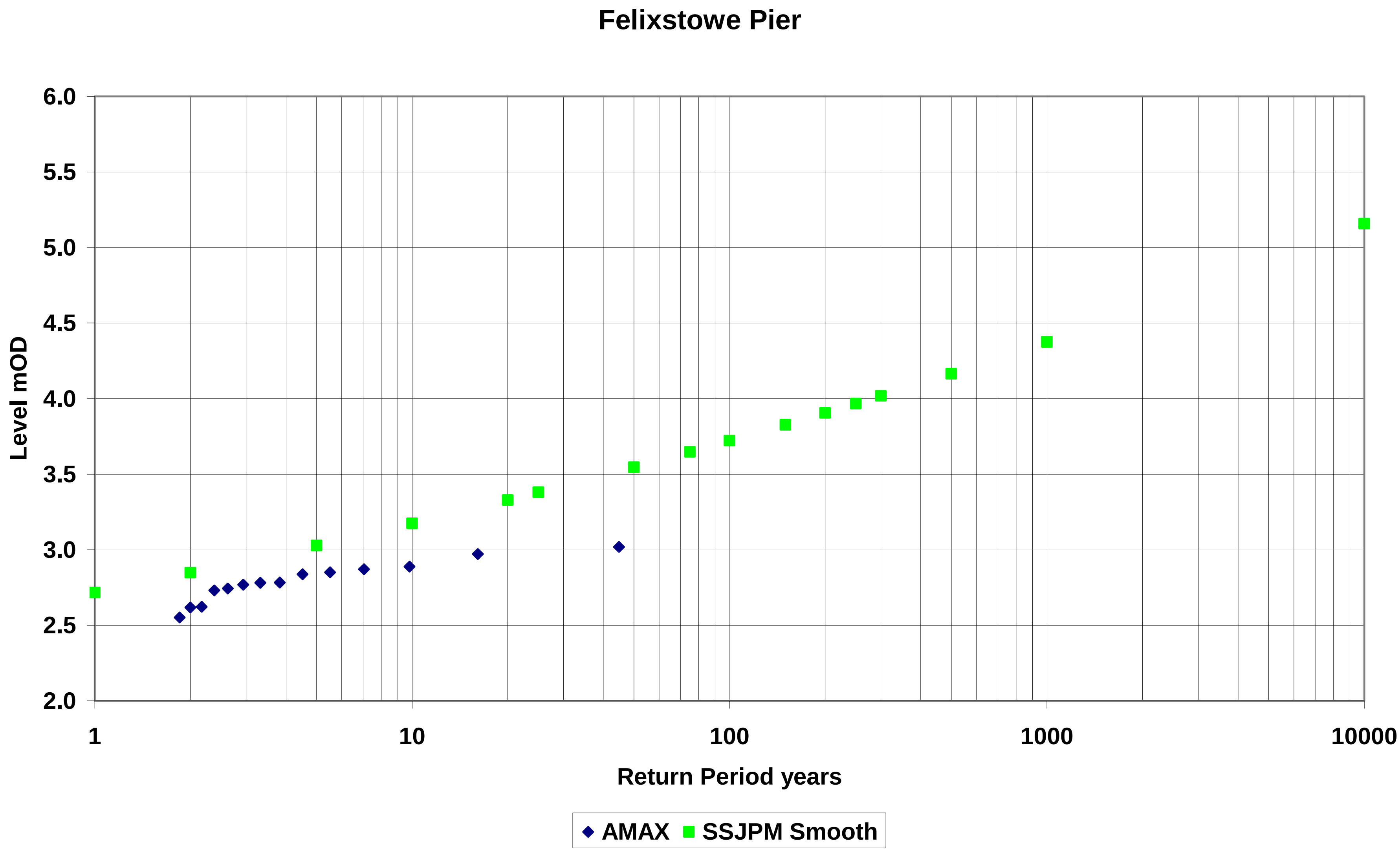

North Shields
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
AMAX
SSJPM


Whitby
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

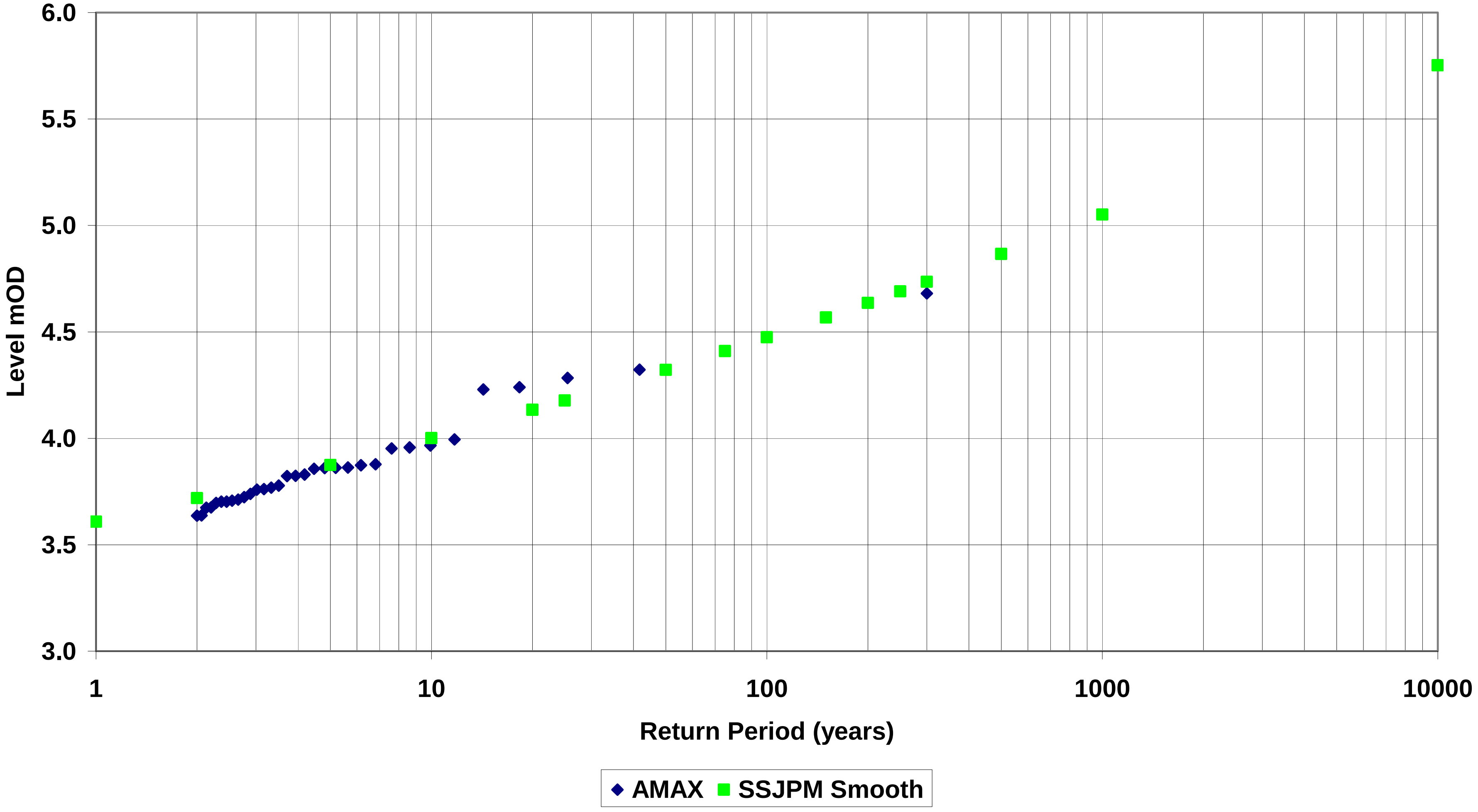

Immingham
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

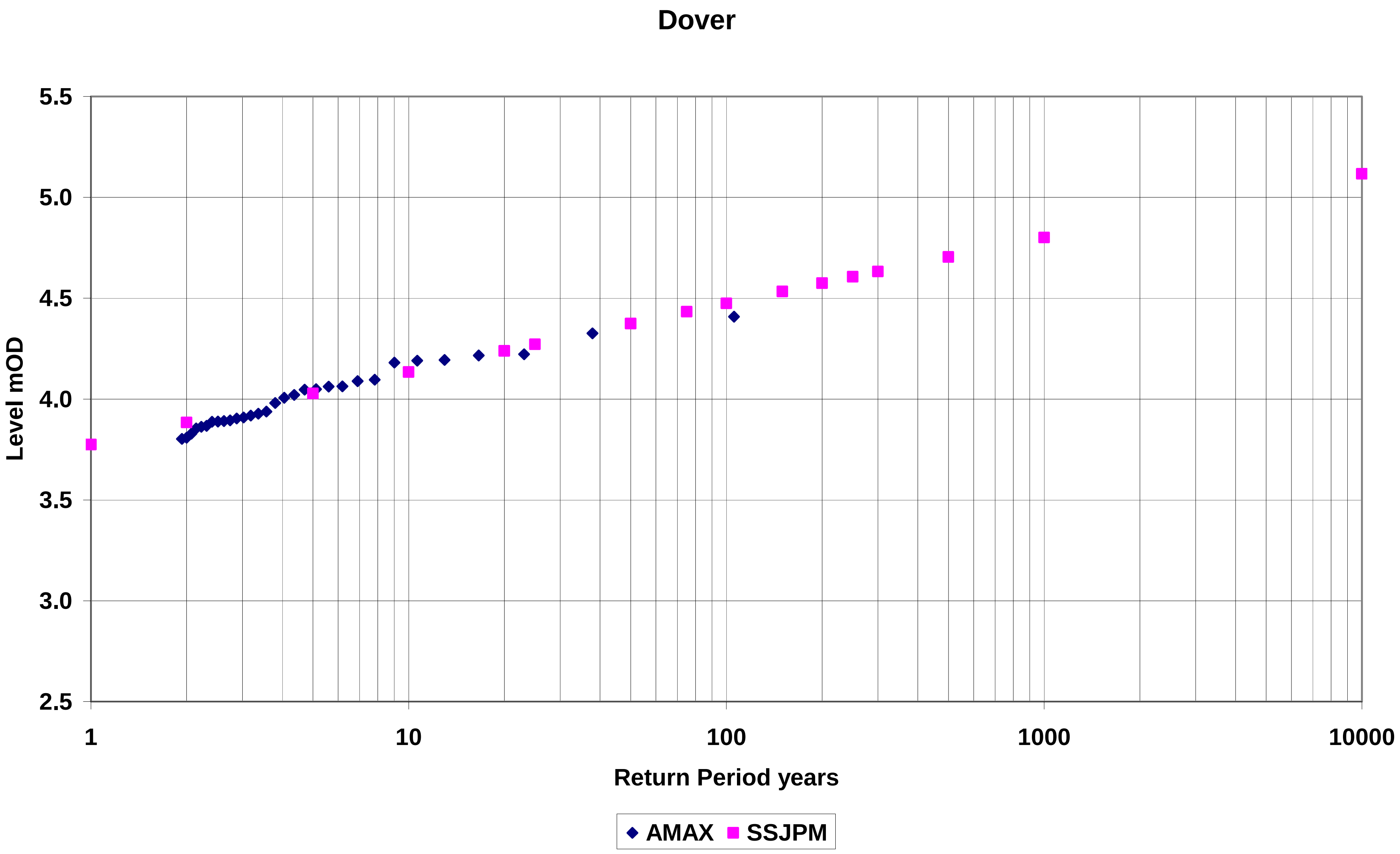

Cromer
Level mOD
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return period years
◆ AMAX
🟩 SSJPM Smooth

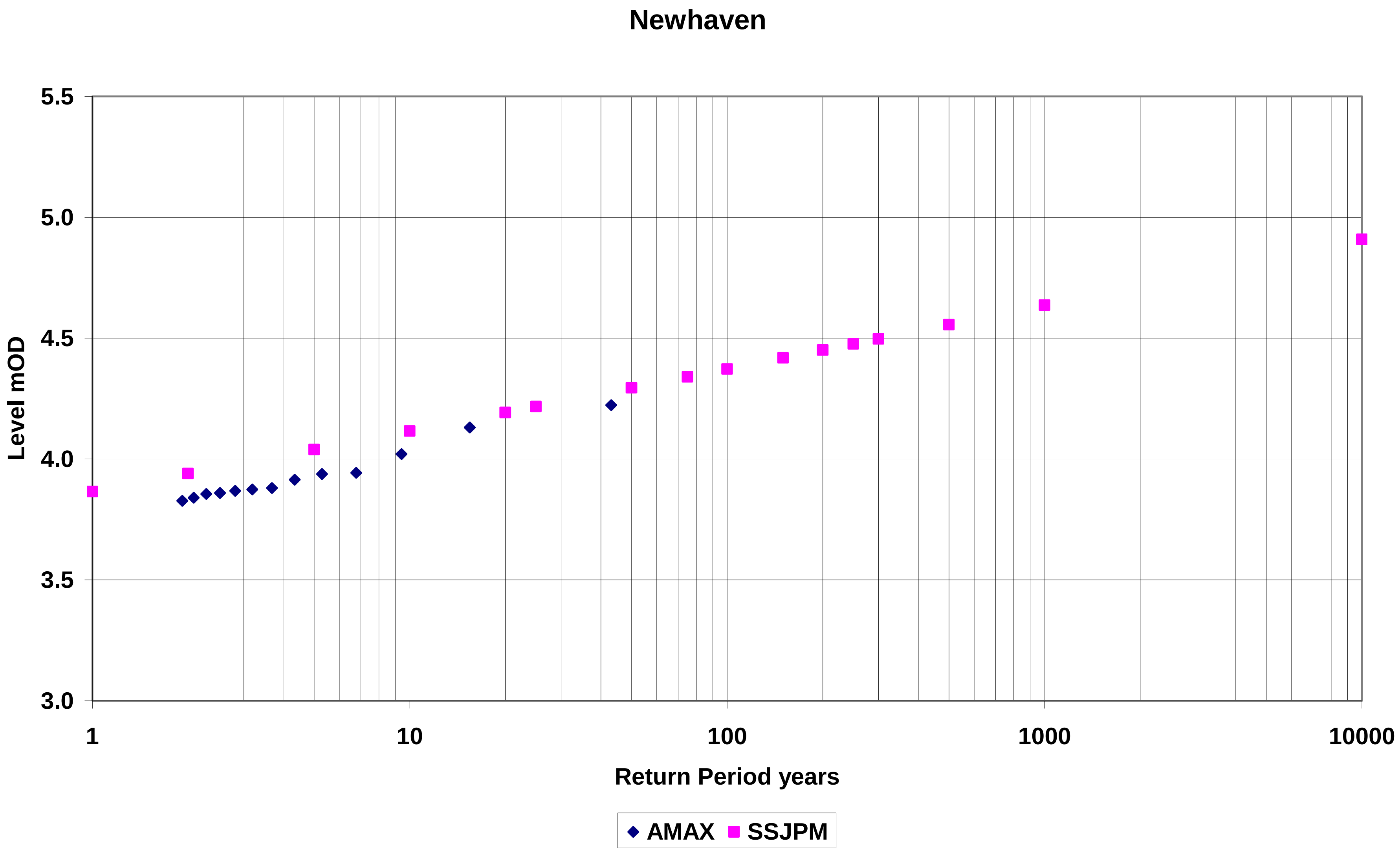

Lowestoft
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ Interpolated

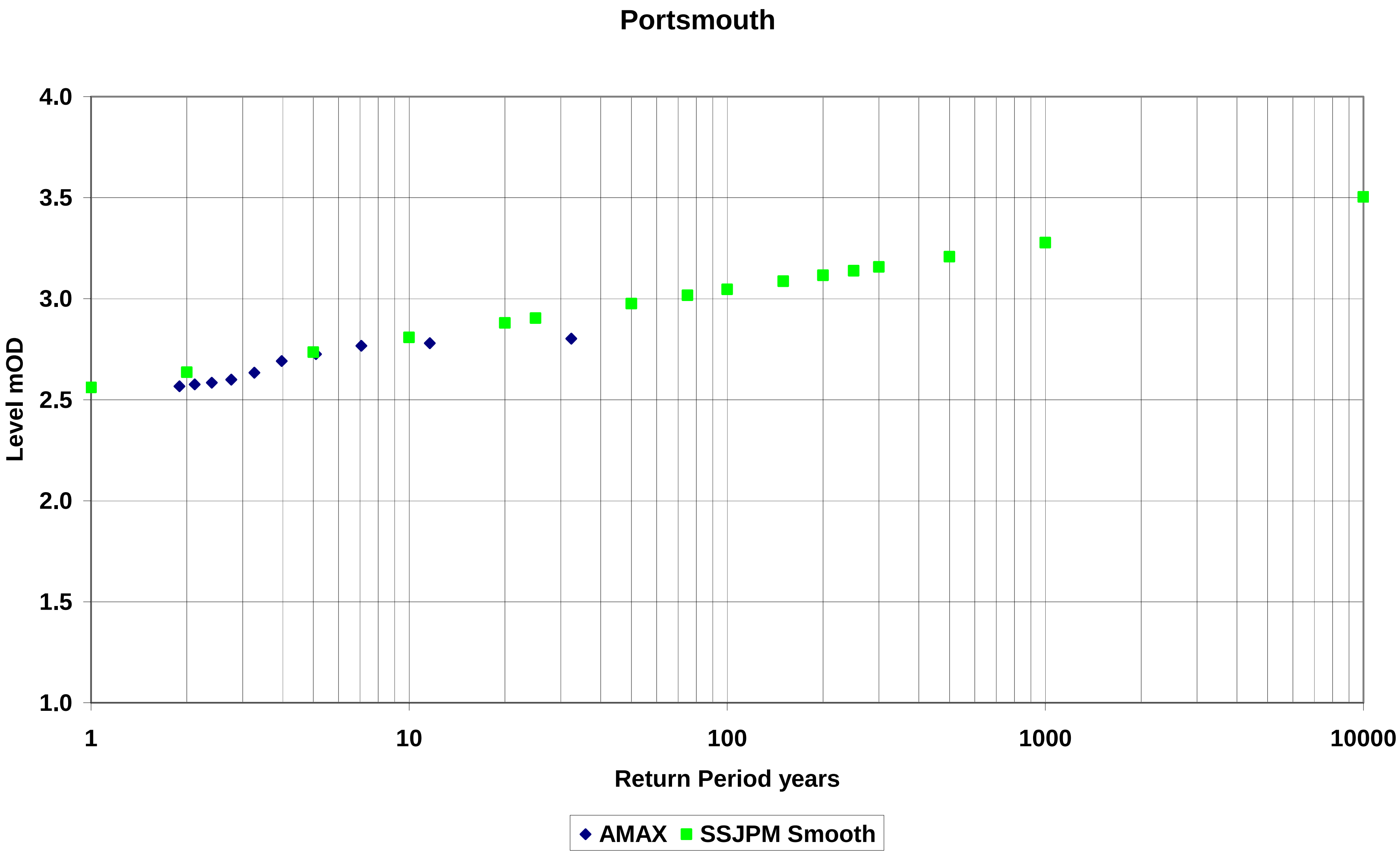

Felixstowe Pier
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX
🟩 SSJPM Smooth

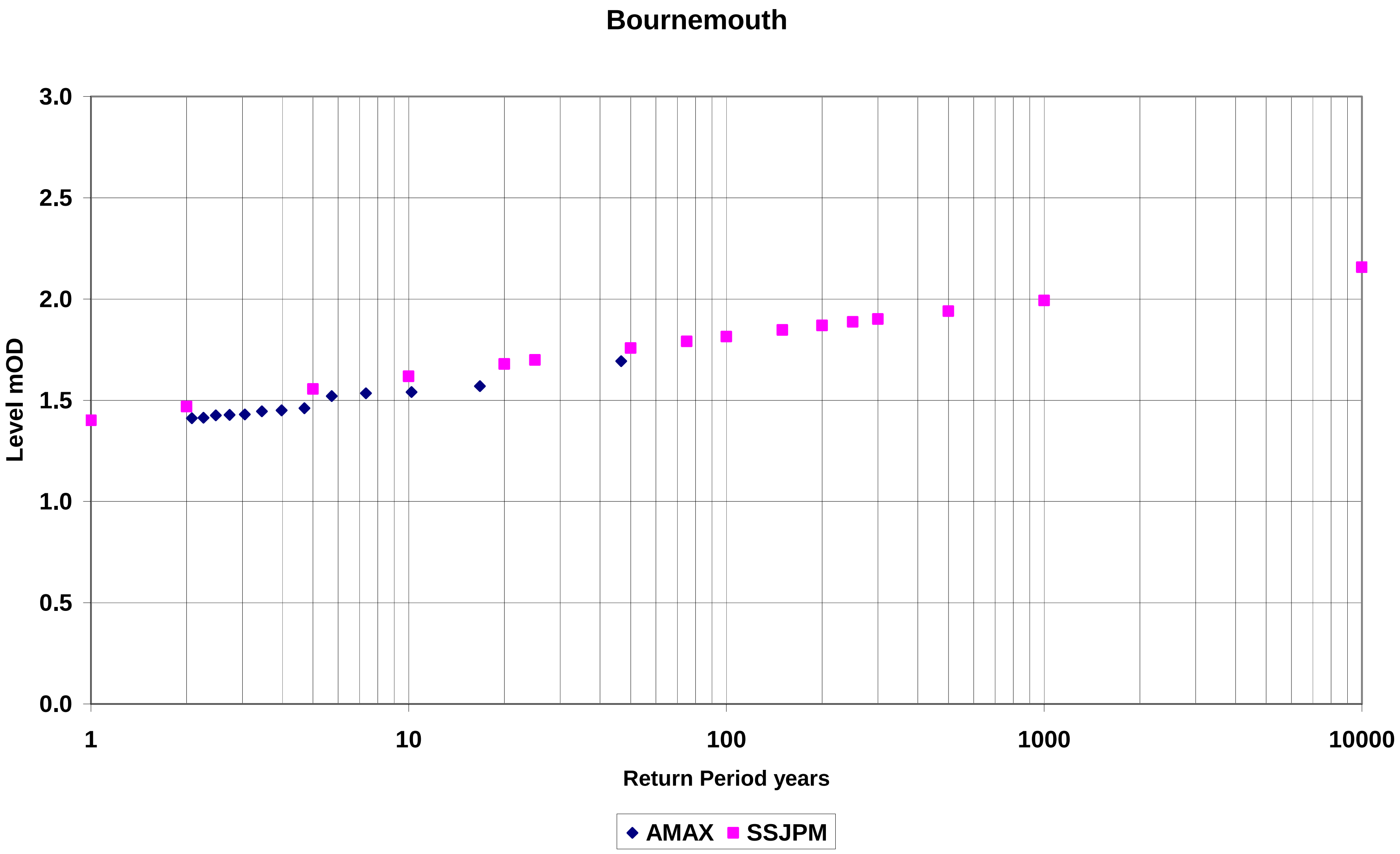
Southend

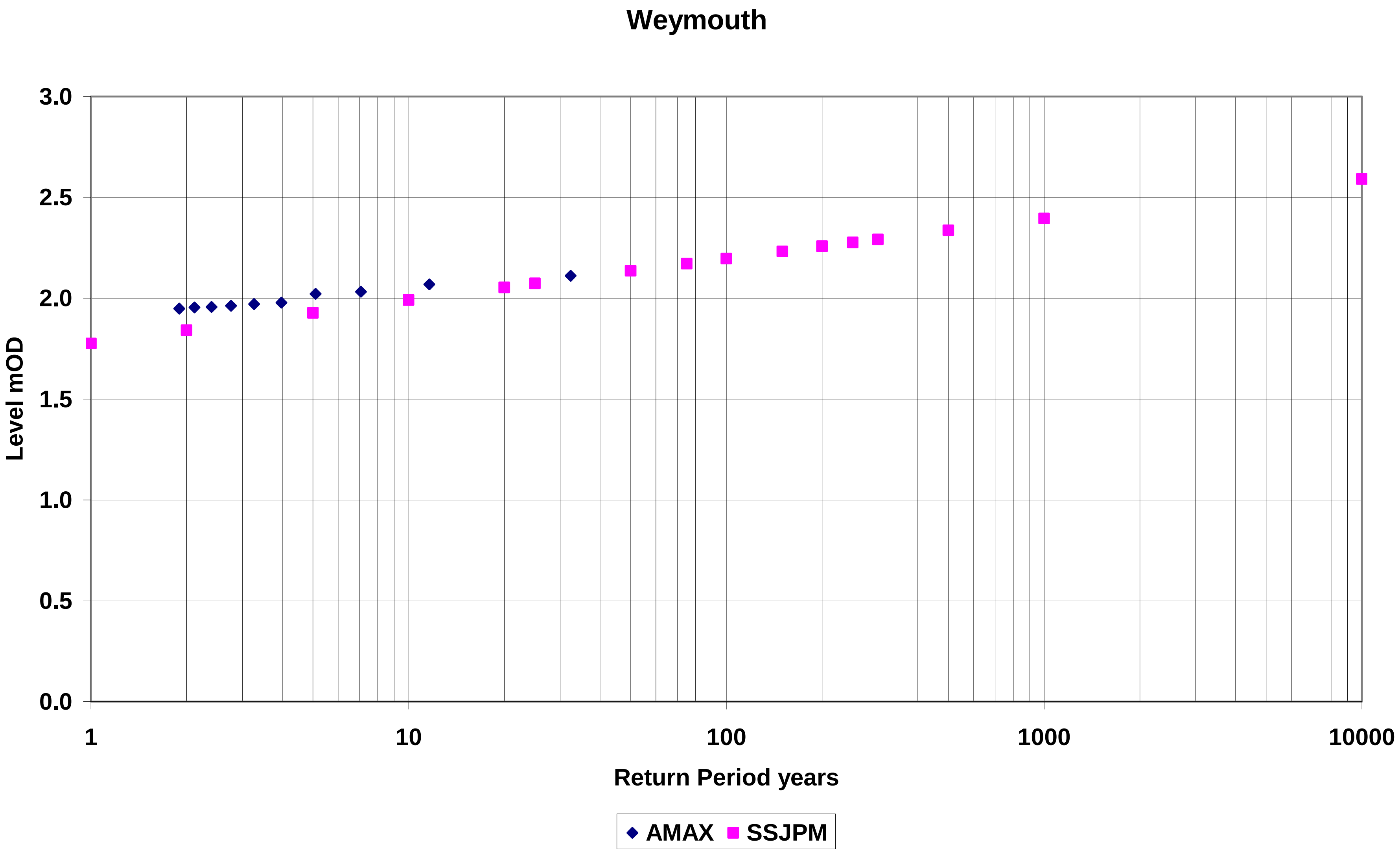

Level mOD
6.0
5.5
5.0
4.5
4.0
3.5
3.0
1
10
100
1000
10000
Return Period (years)
AMAX
SSJPM Smooth

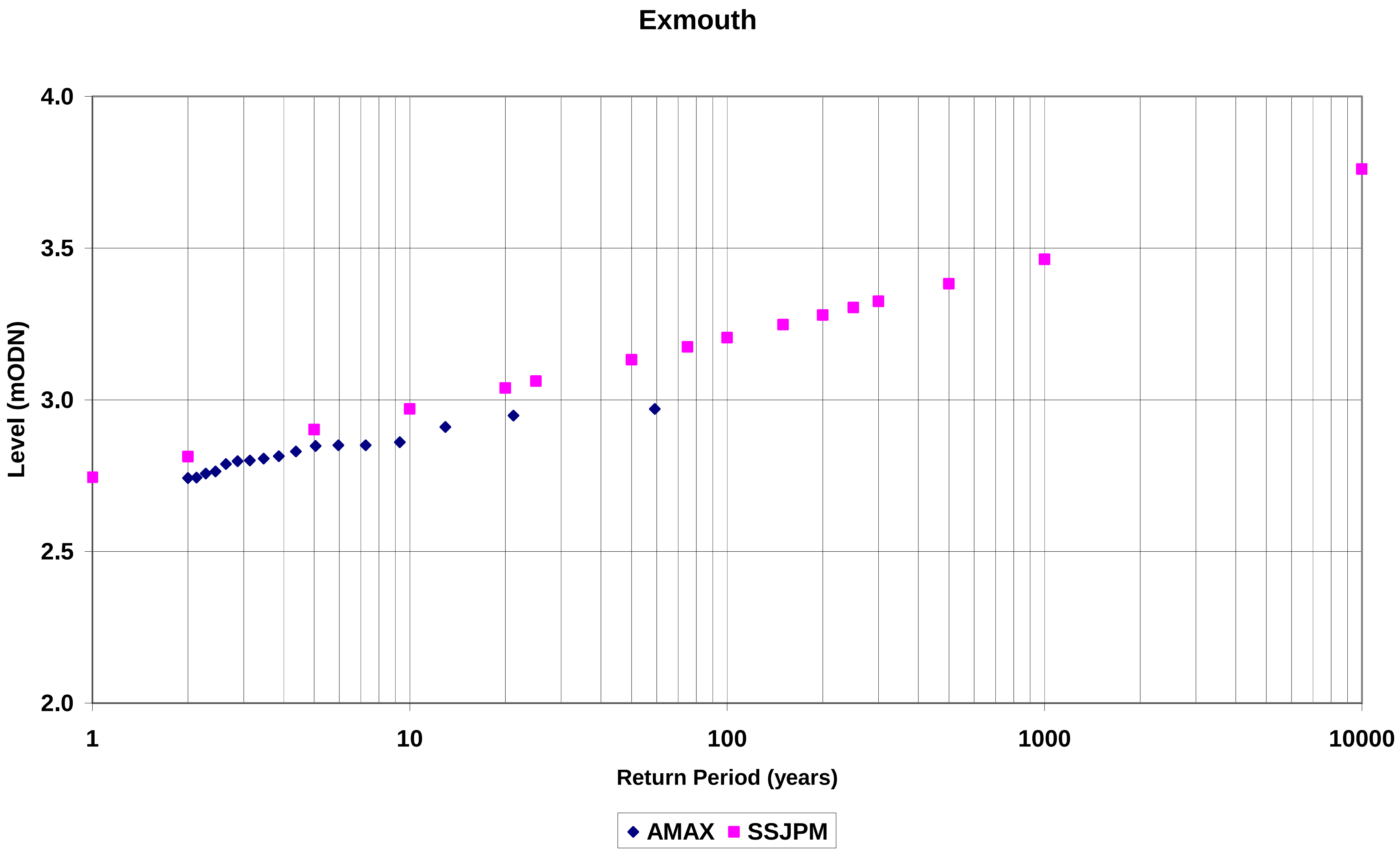

Dover
Level mOD
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

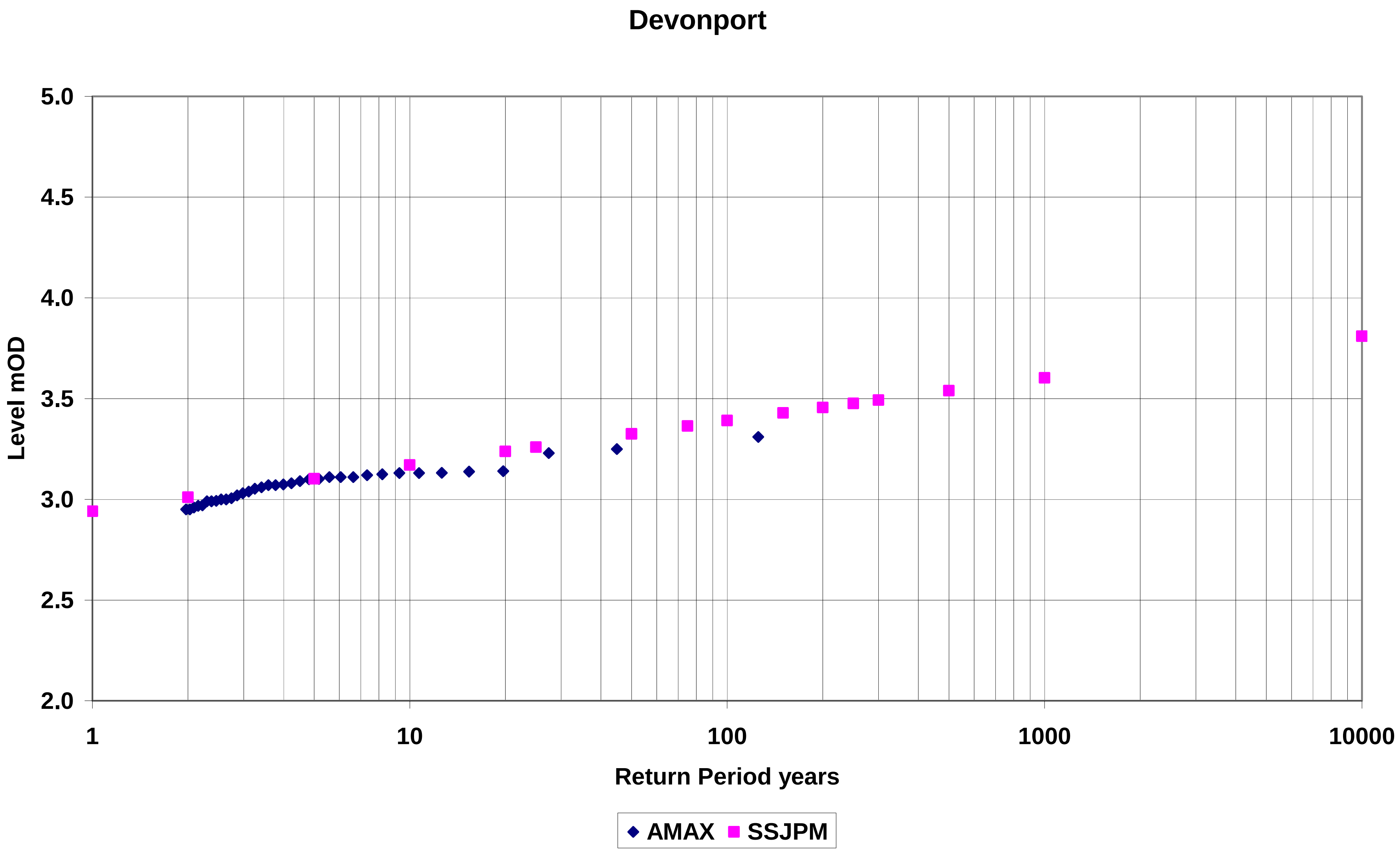

Newhaven
Level mOD
5.5
5.0
4.5
4.0
3.5
3.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM


Portsmouth
4.0
3.5
3.0
2.5
2.0
1.5
1.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX
🟩 SSJPM Smooth


Bournemouth
Level mOD
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM


Weymouth
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Level mOD
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM


Exmouth
4.0
3.5
3.0
2.5
2.0
Level (mODN)
1
10
100
1000
10000
Return Period (years)
◆ AMAX
■ SSJPM


Devonport
Level mOD
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1
10
100
1000
10000
Return Period years
◆ AMAX
■ SSJPM

Appendix 6 Confidence Intervals for the Results

A6.1 Introduction

This appendix presents the approach to providing confidence intervals for all estimates of extreme sea levels. The adopted confidence intervals are based on confidence bounds produced within the statistical analysis.

A6.2 Confidence Bounds

The 95% confidence bounds were calculated for sites where statistical analysis, using the Skew Surge Joint Probability Method, was undertaken. Sites where statistical smoothing was undertaken (as described in **Section 4**) were not included. The statistical smoothing (of the parameters of neighbouring sites) was employed to curtail the implausible growth to lower annual exceedance probability. It was not possible to statistically determine the confidence bounds at these sites.

The method, to derive confidence bounds at statistical analysis sites, involved the generation of numerous time series of skew surge of equal length to the original. These time series were produced by taking random samples from the probability distribution of the skew surge, thereby ensuring the random time series exhibited approximately the same distribution. The resulting 2.5 and 97.5 percentiles of the extreme sea levels were extracted to represent the 95% confidence bounds. **Table A6.1** shows the original confidence bounds using this method:

Following consultation with end users it was recognised that practical confidence intervals are required to assess the uncertainty associated with the estimate of sea levels. In this project we have taken confidence intervals, as being half of the confidence bound width and expressed as a distance (±) from the mean sea level estimate.

The confidence bounds in **Table A6.1** were used as the starting point to develop empirical confidence intervals for all output points along the main chainage line and for selected island chainage points. The approach was guided by the need to be precautionary given the uncertainties and the need to be consistent around the coast, mindful of the geography.

A comparison of confidence bounds for the 1, 0.01 and 0.001 annual exceedance probabilities (1, 100 and 1,000 year return periods) identified a confidence interval minimum as shown in **Table A6.2**.

Table A6.2 – Minimum Confidence Intervals

Return Period (years)	1	10	1,000
Minimum Confidence Interval (m)	0.1	0.2	0.3

Using these minima and the starting points in **Table A6.1** confidence intervals were derived for all sites where SSJPM analysis was undertaken. These are provided in **Table A6.3**. Confidence intervals are given to one decimal place as any finer level of accuracy is not warranted. The sea levels are also only accurate to one decimal place.

They have been quoted to two decimal places for differentiation between nodes along the 2km resolution chainage.

The confidence intervals for the raw SSJPM analysis sites were applied to all results points 50km either side of the site. This 50km buffer was geographically constrained at boundaries between different seas, for example the English Channel and St Georges Channel; Atlantic Ocean and North Sea; and North Sea and English Channel.

Outside of the 50km buffer a further addition was applied, thus increasing the confidence interval further. In the absence of statistical analysis at intermediate sites between the raw SSJPM analysis sites, it was necessary to adopt an empirical approach. Therefore the following additions were applied to the confidence intervals at these locations, as shown in **Table A6.4**.

Table A6.4 – Confidence Interval Add-ons

Confidence Interval (m)	Add-on outside of 50km buffer (m)
0.1 – 0.3	0.1
0.4 – 0.6	0.2
0.7 – 0.9	0.3
1.0 – 1.2	0.4

Where the influence of two primary sites conflicted (i.e. overlapped), a smooth transition between the confidence intervals was introduced to maintain the consistency around the coastline.

We have also provided confidence intervals for the Scottish Islands. In the absence of uncertainty information for a fixed point on some islands, we have adopted an empirical approach to provide confidence intervals. This approach uses the uncertainty information from the main chainage and applies an additional allowance for the islands. This approach was used for the western isles, including Islay and Jura. This approach was also used for the Orkney Islands.

We have used the same information to derive extreme sea levels for the Isle of Arran to that of the main chainage along the Ayrshire and Argyll coastlines. We have therefore taken the same approach to derive confidence intervals for the Isle of Arran.

For the Outer Hebrides we have calculated confidence intervals for Stornaway. We have therefore adopted the same approach as the main chainage, with points within 50km of Stornaway having the same confidence intervals. Outside of this an additional allowance has been added where there is increased uncertainty. Furthermore, we have included an additional uncertainty allowance for the western Outer Hebrides. This coastline is very different to that at Stornaway, therefore we can expect the uncertainty to be slightly greater for these points.

A6.3 Application of Confidence Intervals

A6.3.1 Confidence Intervals at SSJPM Sites

This project has provided estimates of sea levels. Confidence Intervals have been provided for each of these estimates. **Table A6.5** and **Figure A6.1** show how confidence intervals can be applied to the extreme sea level estimates to provide an upper and lower confidence bound. In this example annual exceedance probabilities ranging from 1 to 0.0001 (1 year to 1,000 year return periods) are provided for Aberdeen (Chainage 3226km):

Table A6.5 – Confidence Intervals at Aberdeen (Chainage 3226km)

Return Period (years)	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1000**	**10000**
Sea Level (mOD)	2.68	2.75	2.84	2.91	2.97	2.99	3.05	3.09	3.11	3.14	3.17	3.18	3.20	3.24	3.29	3.45
Confidence Interval (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Lower Bound (m)	2.58	2.65	2.74	2.81	2.87	2.89	2.95	2.99	2.91	2.94	2.97	2.98	3.00	3.04	2.99	3.15
Upper Bound (m)	2.78	2.85	2.94	3.01	3.07	3.09	3.15	3.19	3.31	3.34	3.37	3.38	3.40	3.44	3.59	3.75

A6.3.2 Confidence Intervals away from SSJPM Sites

Outside the influence of the raw SSJPM analysis site Confidence Intervals further additions are required, as discussed previously. **Table A6.6** and **Figure A6.2** show the further allowance of confidence intervals outside of the 50km SSJPM buffer for Chainage 3084km.

Table A6.6 – Confidence Intervals including add-ons (Chainage 3084km)

Return Period (years)	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1000**	**10000**
Sea Level (mOD)	2.60	2.66	2.74	2.81	2.86	2.89	2.95	2.98	3.00	3.04	3.06	3.09	3.10	3.15	3.21	3.44
Confidence Interval (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
50km add-on (m)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Upper Bound (m)	2.40	2.46	2.54	2.61	2.66	2.69	2.75	2.78	2.70	2.74	2.76	2.79	2.80	2.85	2.81	3.04
Upper Bound (m)	2.80	2.86	2.94	3.01	3.06	3.09	3.15	3.18	3.30	3.34	3.36	3.39	3.40	3.45	3.61	3.84

Table A6.1 – Original 95% Confidence Bounds for SSJPM sites

	Return Period Confidence Bounds (m)															
Gauge Site	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1000**	**10000**
Newlyn	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.09	0.16
St Mary's	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.10	0.13	0.16	0.34
Ilfracombe	0.01	0.01	0.02	0.03	0.04	0.05	0.07	0.08	0.09	0.11	0.13	0.15	0.16	0.20	0.28	0.68
Mumbles	0.02	0.03	0.05	0.08	0.10	0.11	0.19	0.27	0.33	0.41	0.48	0.53	0.57	0.72	0.94	1.96
Milford Haven	0.01	0.02	0.03	0.04	0.06	0.07	0.09	0.11	0.13	0.16	0.18	0.19	0.21	0.25	0.32	0.70
Fishguard	0.01	0.01	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.11	0.12	0.13	0.13	0.16	0.21	0.49
Barmouth	0.05	0.07	0.09	0.10	0.13	0.15	0.18	0.20	0.22	0.26	0.29	0.31	0.32	0.38	0.46	0.79
Holyhead	0.02	0.02	0.03	0.04	0.05	0.06	0.07	0.09	0.10	0.12	0.14	0.15	0.16	0.19	0.24	0.45
Llandudno	0.02	0.03	0.05	0.07	0.09	0.10	0.15	0.19	0.22	0.27	0.31	0.35	0.37	0.46	0.60	1.34
Hilbre Island	0.00	0.01	0.01	0.02	0.04	0.05	0.08	0.10	0.12	0.15	0.18	0.20	0.21	0.27	0.36	0.89
Port Erin	0.04	0.05	0.06	0.08	0.10	0.11	0.14	0.16	0.18	0.21	0.23	0.25	0.26	0.30	0.36	0.61
Portpatrick	0.03	0.04	0.06	0.07	0.10	0.11	0.14	0.15	0.17	0.18	0.20	0.21	0.23	0.26	0.31	0.49
Millport	0.09	0.11	0.17	0.25	0.33	0.38	0.51	0.61	0.69	0.79	0.86	0.92	0.98	1.14	1.37	2.38
Tobermory	0.04	0.07	0.10	0.15	0.21	0.24	0.30	0.35	0.40	0.48	0.55	0.61	0.66	0.82	1.06	2.14
Ullapool	0.02	0.03	0.04	0.05	0.06	0.06	0.08	0.09	0.09	0.10	0.11	0.12	0.13	0.14	0.17	0.31
Stornoway	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.10	0.12	0.15	0.27
Kinlochbervie	0.03	0.04	0.07	0.10	0.14	0.16	0.23	0.26	0.30	0.37	0.43	0.48	0.52	0.64	0.82	1.63
Wick	0.02	0.03	0.04	0.05	0.07	0.07	0.09	0.11	0.11	0.13	0.14	0.15	0.16	0.19	0.24	0.44
Lerwick	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.09	0.11	0.14	0.24
Aberdeen	0.01	0.02	0.03	0.04	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.09	0.10	0.12	0.20
Leith	0.02	0.03	0.05	0.09	0.14	0.16	0.25	0.30	0.34	0.41	0.46	0.51	0.55	0.66	0.84	1.70
North Shields	0.02	0.03	0.05	0.07	0.10	0.12	0.16	0.19	0.22	0.26	0.30	0.32	0.35	0.42	0.53	1.00
Whitby	0.03	0.05	0.09	0.14	0.20	0.22	0.30	0.36	0.41	0.49	0.54	0.58	0.62	0.75	0.93	1.81
Immingham	0.03	0.04	0.06	0.08	0.12	0.13	0.18	0.22	0.25	0.29	0.32	0.35	0.37	0.45	0.55	0.99
Dover	0.04	0.05	0.07	0.09	0.11	0.12	0.15	0.18	0.20	0.23	0.24	0.26	0.28	0.32	0.38	0.63
Newhaven	0.02	0.03	0.04	0.06	0.08	0.09	0.12	0.15	0.17	0.20	0.22	0.24	0.26	0.32	0.40	0.71
Portsmouth	0.04	0.05	0.06	0.07	0.09	0.09	0.12	0.14	0.15	0.17	0.19	0.20	0.21	0.24	0.28	0.42
Bournemouth	0.04	0.06	0.08	0.10	0.14	0.15	0.19	0.22	0.24	0.26	0.28	0.29	0.31	0.35	0.42	0.70
Weymouth	0.03	0.04	0.06	0.07	0.10	0.11	0.14	0.17	0.19	0.22	0.23	0.25	0.26	0.30	0.35	0.59
Exmouth	0.04	0.05	0.08	0.10	0.15	0.16	0.22	0.27	0.32	0.38	0.43	0.47	0.51	0.61	0.75	1.38
Devonport	0.03	0.04	0.06	0.07	0.09	0.10	0.14	0.18	0.20	0.23	0.25	0.27	0.28	0.33	0.39	0.74

Table A6.3 – Modified Confidence Intervals for Raw SSJPM Sites

	Return Period Confidence Intervals (m)															
Gauge Site	**1**	**2**	**5**	**10**	**20**	**25**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**500**	**1000**	**10000**
Newlyn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
St Mary's	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Ilfracombe	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Mumbles	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.5	1
Milford Haven	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Fishguard	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Barmouth	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Holyhead	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Llandudno	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.7
Hilbre Island	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5
Port Erin	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Portpatrick	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Millport	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.7	1.2
Tobermory	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	1.1
Ullapool	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Stornoway	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Kinlochbervie	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.5	0.9
Wick	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Lerwick	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Aberdeen	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Leith	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.5	0.9
North Shields	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.5
Whitby	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.5	1
Immingham	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.5
Dover	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Newhaven	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Bournemouth	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4
Weymouth	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
Exmouth	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.7
Devonport	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4

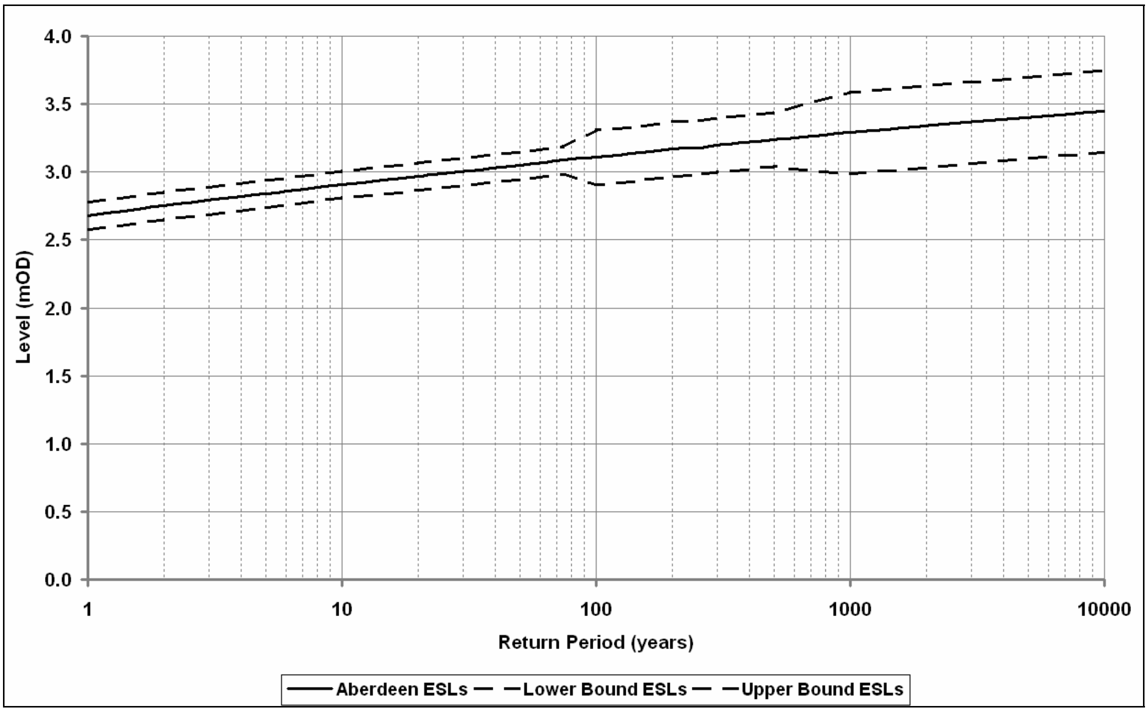


Figure A6.1 – Application of Confidence Intervals at Chainage 3226km

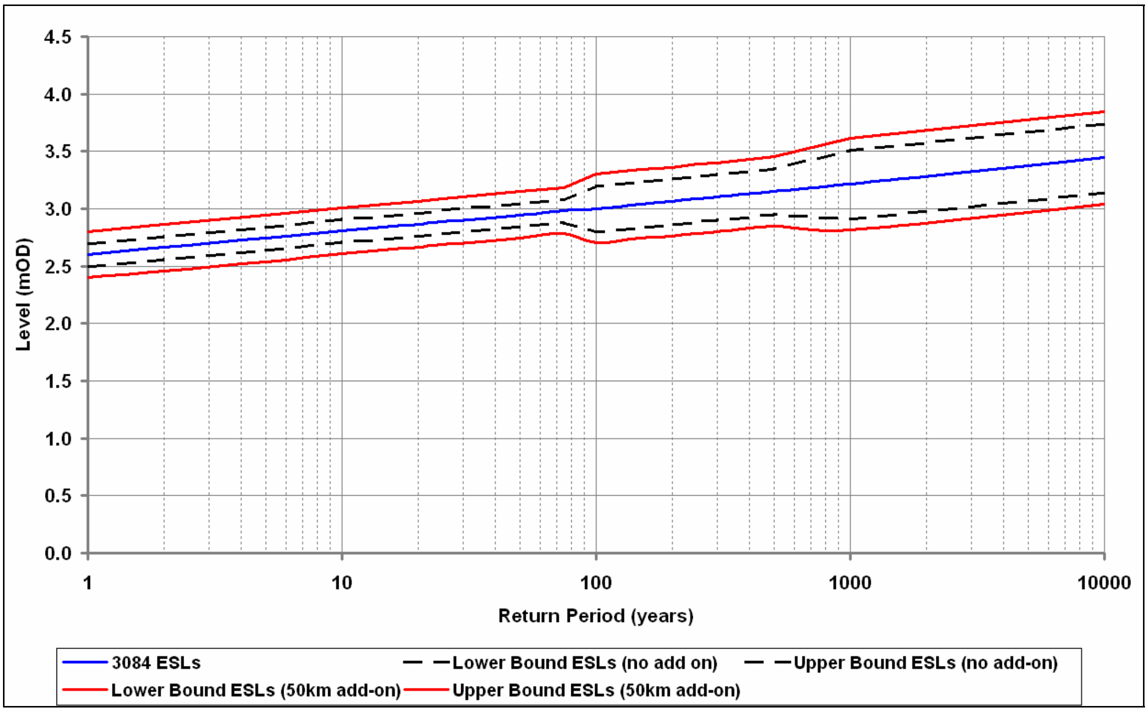


Figure A6.2 – Application of Confidence Intervals at Chainage 3084km

Appendix 7 Design Surge Curves

A7.1 Introduction

In addition to estimates of peak extreme sea-levels, 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 and 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. An illustration of a design tidal-graph is given in **Figure A7.1**. In this plot, the red line represents the underlying Astronomical Tide (referred to as Tide hereafter), the black line represents the progression of a Storm Surge (quantified here by Surge Residual), and the blue line represents the Observed or Total Sea-Level (referred to as Total Sea-Level hereafter), which is principally the combination of the Tide and the Storm Surge but may also include Wind Set-Up.

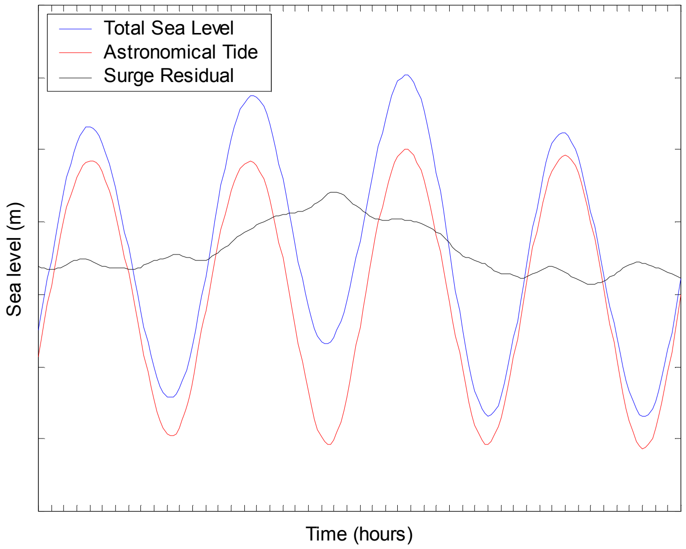


Figure A7.1 Example design tidal-graph (illustrating Surge Residual)

This appendix details how design surge shapes have been derived, based on an analysis of recorded data from the UK Class A tide gauge network.

Sections 2 and 3 of the Appendix outline the science and research carried out as part of the project.

A7.2 Development of design surge shapes

The key component of a design tidal-graph is a 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.

A7.2.1 Surge Residual versus Skew Surge

As discussed in the main report, surges can be defined numerically in two ways: Surge Residual (as in **Figure A7.1**) and Skew Surge (**Figure A7.2**)[1]. Many practitioners have developed design surge shapes in the past using the variable Surge Residual; a variable which is easily accessible from many tide gauge records.

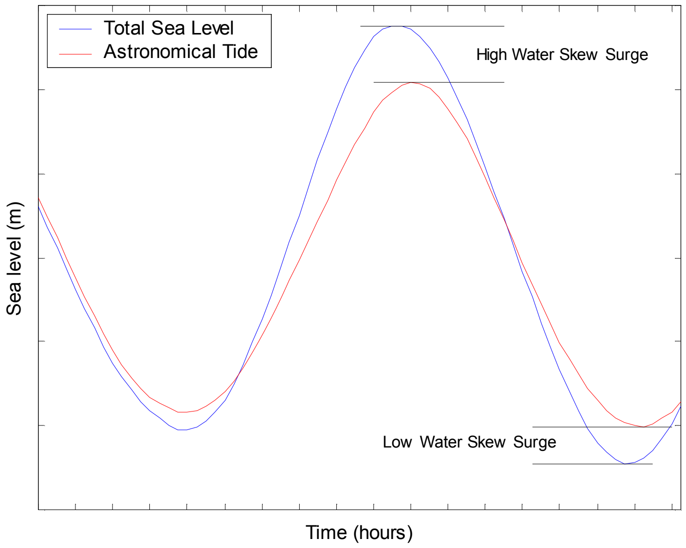


Figure A7.2 Example design tidal-graph (illustrating Skew Surge)

Surge Residual values are not necessarily a reflection of true tidal surge but can arise fully, or in part, due to phase differences (i.e. 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, as shown in **Figure A7.3**.

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[1] 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.

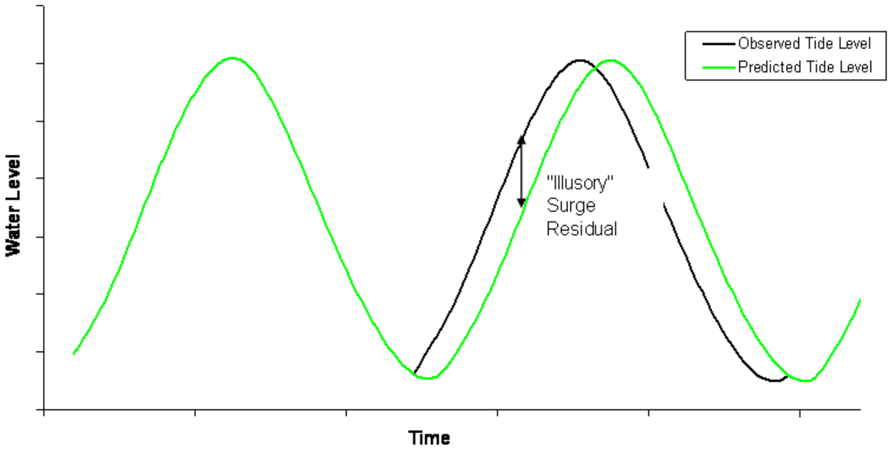

Figure A7.3 Illusory Surge Residual

This “illusory” surge is often most apparent at the mid-tide stage, where the change in level with time is at its greatest, so any phase difference will inevitably give the most pronounced surge residual. An example is shown in **Figure A7.4**.

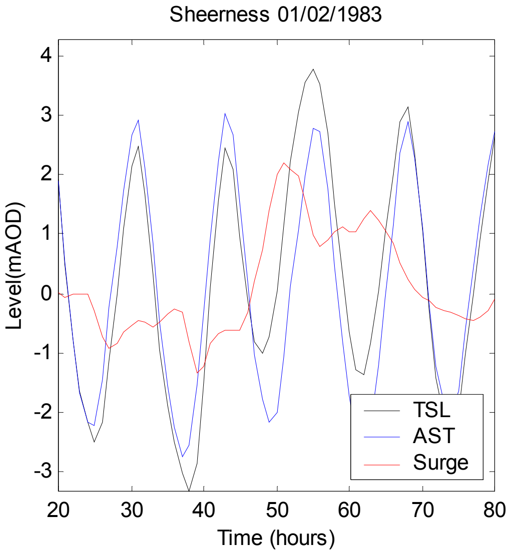

Figure A7.4 Example of the tendency for Surge Residual profiles to peak at mid-tide

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 has been adopted in this study for the generation of design surges. **Figure A7.5** illustrates that unlike Surge Residuals, there is no noticeable correlation between Skew Surge magnitude and Tide Level magnitude for Sheerness. This lack of correlation is also apparent for all of the other tide gauge sites used in this study. 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.

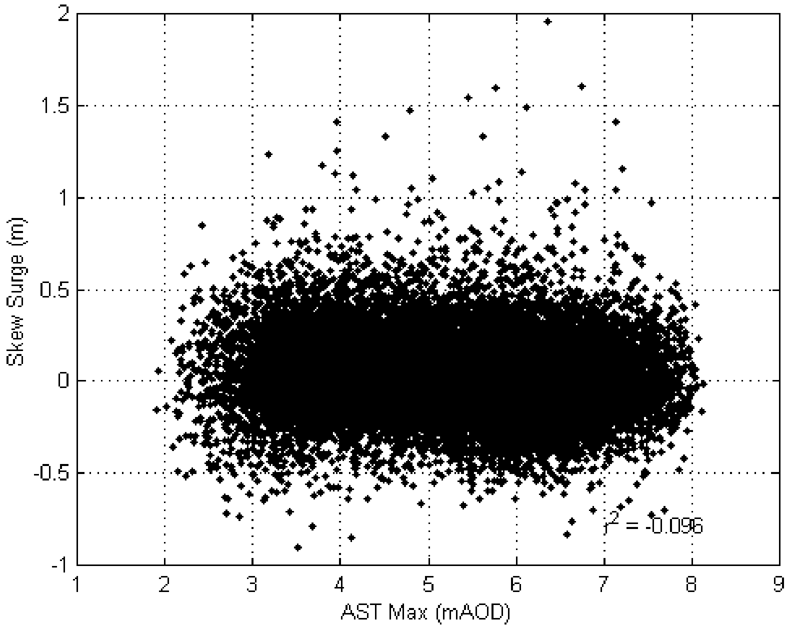

Figure A7.5 Skew Surge magnitude versus peak Tide Level (AST Max)

A7.2.2 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 40 Class A Tide Gauges sites in England, Wales and Scotland. From this 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 A7.2**). To interpolate these values to a higher temporal frequency (15 minute), a number of interpolation schemes were implemented, including cubic spline interpolation and a form of moving average interpolation.

Figure A7.6 provides examples of the surges extracted and interpolated for Aberdeen. 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 (less than 0.40 mOD) noise, before and after the primary peak. Because each of the events illustrated in **Figure A7.6** has a different peak magnitude, the similarity in the profile shapes is somewhat masked. In **Figure A7.6** each of the 15 largest events for the same three sites has been 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 also been removed for clarity.

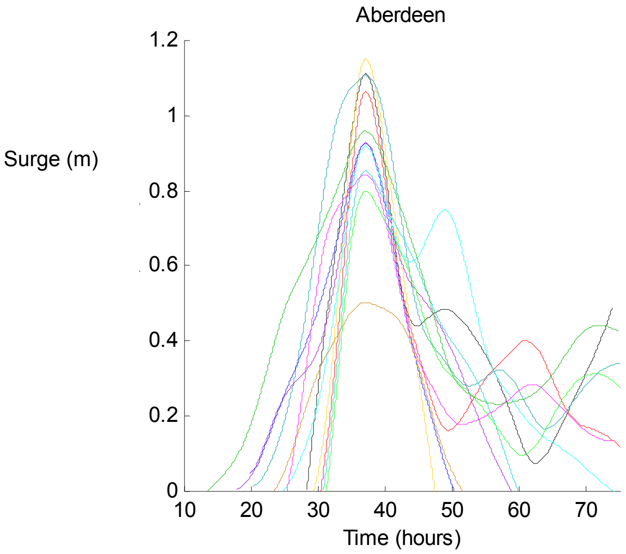

Figure A7.6 Example of large surges profiles for Aberdeen

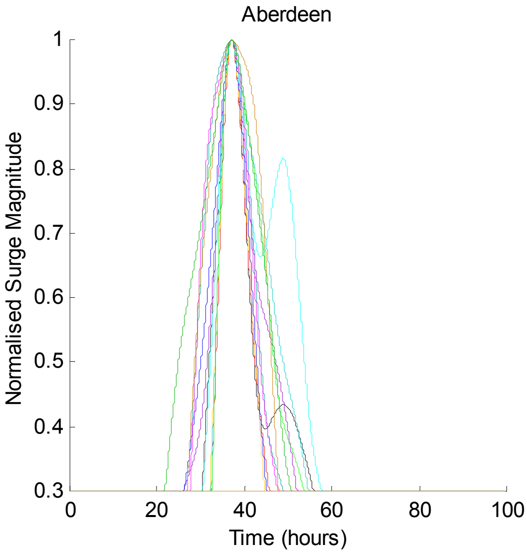

Figure A7.7 Example of large surges profiles normalised to a value of 1 for Aberdeen

Whilst there is clearly similarity in form of the surge profiles shown in **Figure A7.6** and **Figure A7.7**, there is also diversity. Consequently, deriving one design surge shape to represent an area for modelling purposes requires some form of generalisation. Clearly, the generalised surge shape adopted for a site must conform with observations to ensure that it is a realistic representation of local processes but 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 as part of this study to derive potential design surge shapes. The potential design surge shape types derived were:

- An “Average Surge”, based on the average of the 15 largest normalised surges for a site, with obvious outliers removed (**Figure A7.8**)

- An “Envelope Surge”, based on the maximum extent of the 15 largest normalised surges for a site, with obvious outliers removed and various smoothing algorithms applied (**Figure A7.8**);

- A “Worst Case Surge”, based on the worst case normalised surge of the 15 extracted in terms of “area under the curve” (**Figure A7.8**), and;
- “Time-Integrated Duration Surge” (**Figure A7.8**). To generate this type of surge, the duration of each of the 15 surges (excluding outliers) at particular levels in the surge column (i.e. 10% level, 20% level, etc) was first calculated. The maximum duration at each level in the surge column was then determined. The maximum durations were then 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.

Whilst each of the above methods indeed provides a reasonable means to derive a design surge profile, the “Time-Integrated Duration Surge” method was adopted for the study. It was felt that the “Average Surges” were not suitably conservative given the sample, whilst the “Envelope Surges” were too conservative and not representative of real surge shapes. The “Worst Cast Surges” were also ruled out given that these surges were often very dissimilar to the rest of the sample. The “Time-Integrated Duration Surges” were adopted on the premise that they provided the best representation of the largest surges, both in terms of shape and duration. **Figure A7.9** illustrates examples of the “Time-Integrated Duration Surges” adopted as the design surges from this study at Aberdeen. Cromer, Dover and Heysham. The grey lines in these plots illustrate the 15 normalised largest surges exported and interpolated for each site (note: as discussed above some outliers were removed in the analysis).

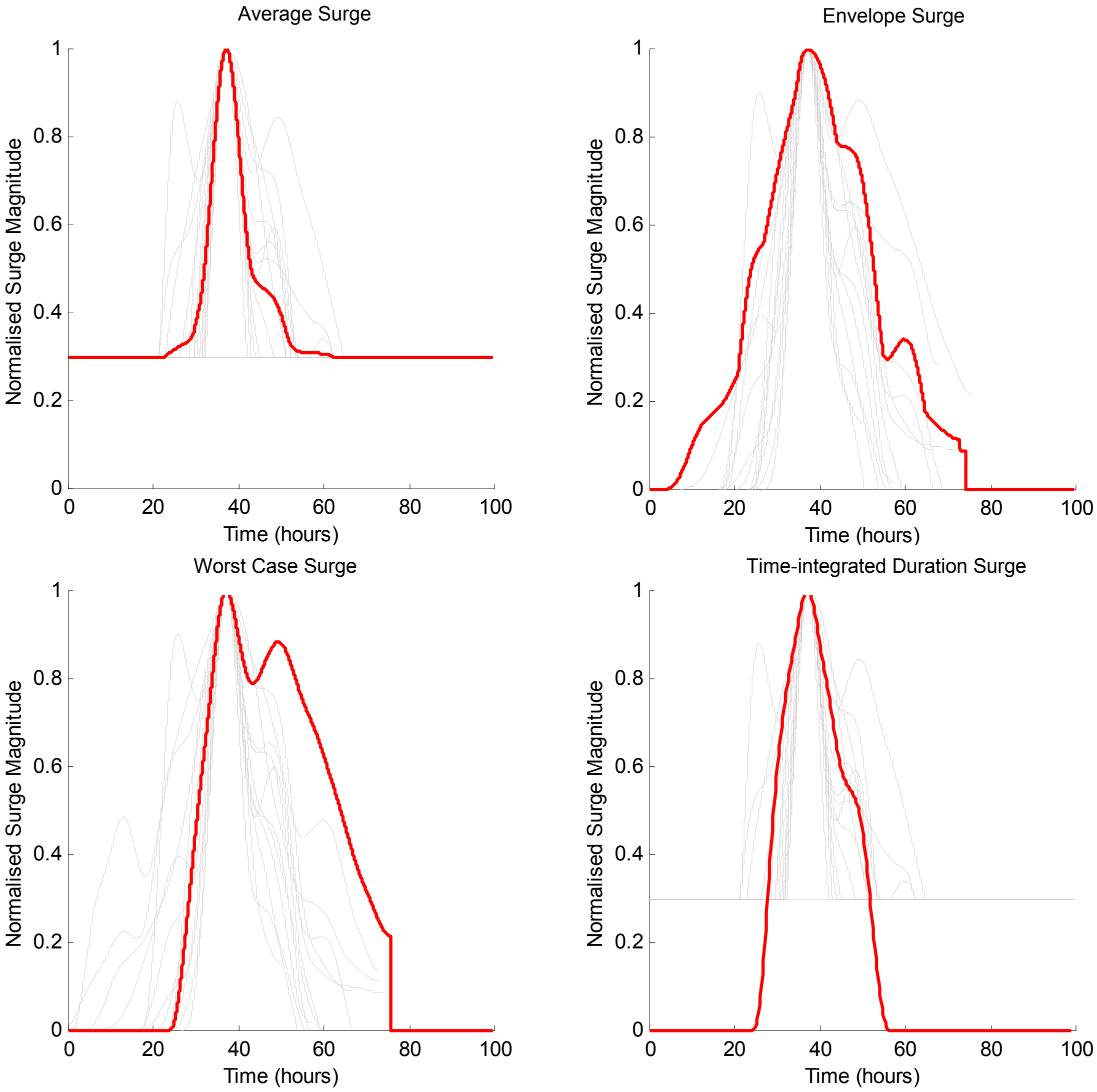

Figure A7.8 Potential design surge methods, illustrated for Cromer

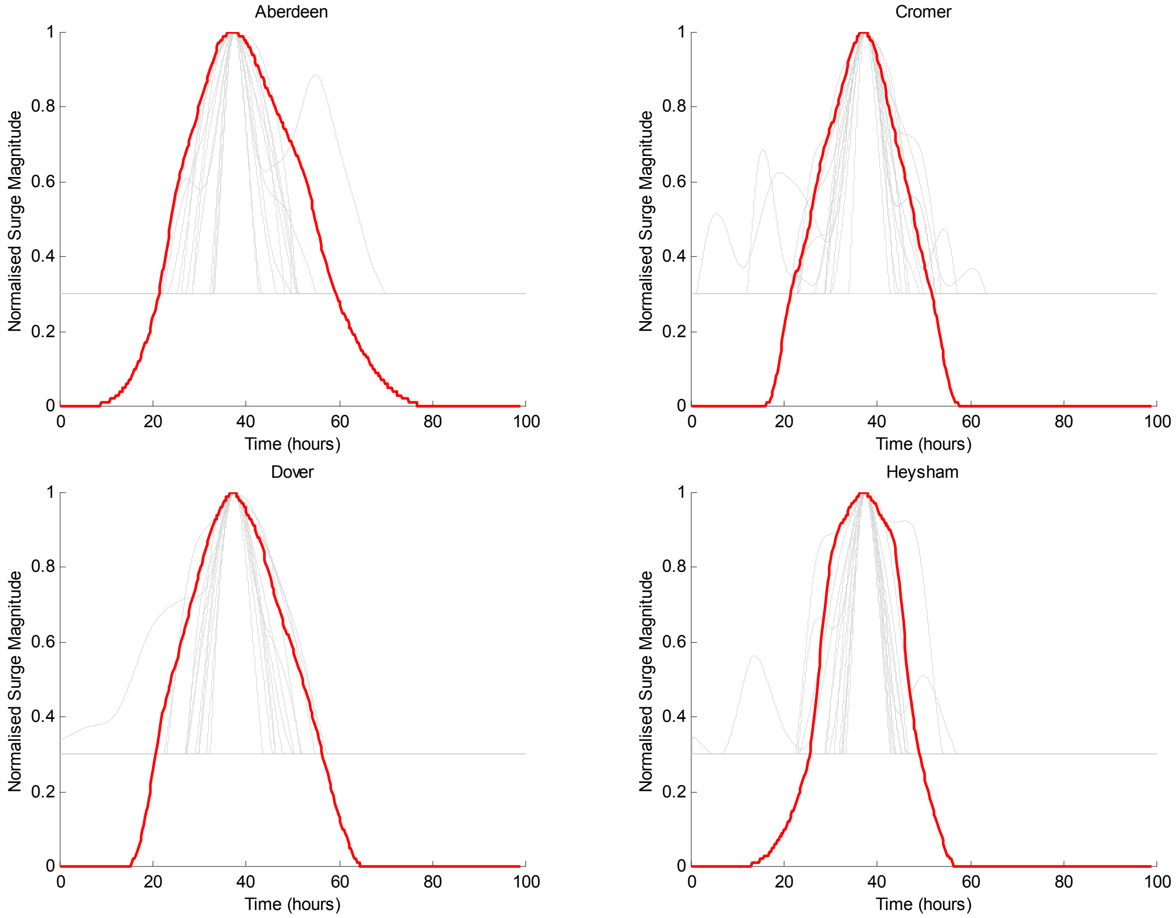

Figure A7.9 Final design surge shapes for Aberdeen, Cromer, Dover and Heysham

A7.2.3 Where to apply the design surge shapes

There is some evidence of similarity of form in the final design surge shapes shown in 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 Class A Tide Gauge site. **Table A8.1** 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, and 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 A8.1 Where to apply the Donor Surge Shapes

Surge Profile	Donor site	Apply from (clockwise around UK):
1	Wick	John o' Groats to Brora
2	MorayFirth	Brora to Lossiemouth (Moray Firth)
3	Aberdeen	Lossiemouth to Arbroarth
4	Leith	Arbroarth 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 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 (Morecambe Bay, Duddon Estuary)
31	Workington	Haverigg Point to Isle of Withorn (Solway Firth, Wigtown Bay)
32	Port Erin	Isle of Man
33	Portpatrick	Isle of Withorn to Girvan
34	Millport	Girvan to Mull of Kintyre (incl. Arran)
35	PortEllen	Mull of Kintyre to Oban (incl. Islay, Jura, Colonsay)
36	Tobermory	Oban to Kyle of Lochalsh (incl. Tiree, Coll, Mull, Rhum, Eigg and Skye)
37	Ullapool	Kyle of Lochalsh to Point of Stoer

Table A8.1 Where to apply the Donor Surge Shapes

38	Kinlochbervie	Point of Stoer to John o' Groats
39	Stornoway	Outer Hebrides
40	Lerwick	Orkney Islands, Shetland Islands

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