ESTIMATES OF EXTREME SEA CONDITIONS

Final Report

SPATIAL ANALYSES FOR THE UK COAST

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CONTRACT

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Summary

In this report the third of a three stage analysis of extreme sea-levels around the UK is described. This stage concerns the extension of the methods for the statistical analysis of extreme sea-levels, as described in the first two stages, to incorporate the data from a long run of a hydrodynamical model and to provide design level estimates at regular intervals around the entire mainland UK coast. For the west and south coasts, these spatial estimates are the only estimates available; for the east coast, they should provide improved estimates to those given in the second stage of the work.

Topics covered

- Preliminary summaries of the numerical model data to highlight features of interest.
- Handling of trends in the numerical model data and site data.
- Use of the numerical model data to pinpoint erroneous observational data, which previously have not been detected. Evaluating the effects of removing the erroneous data.
- Development of methods to calibrate numerical model data, based on the observational data. This is needed to correct for any systematic biases in the numerical model data.
- Application of the Spatial Revised Joint Probabilities method (SRJPM) to the adjusted numerical model data: at a regular grid of 89 points around the coast given by the numerical model.
- Development of methods, with full results, giving return level estimates around the entire coastline, on a 20km grid.
- Development of methods to incorporate high resolution numerical model data in order to more reliably estimate return levels in complex coastal regions. Application to the Severn estuary and Bristol Channel.
- Assessment of risk in terms of protection offered by existing structure designs.
- Assessment of encounter risk: the design height required for an acceptable structure lifetime failure probability.

Findings and Conclusions

Results, in the form of return levels for a specific year, 1990, and formulae for calculation for other years are given for a regular grid around the UK. A spatial sea-level trend estimate is obtained for all coastlines including the South and West. The trend is generally positive, around 1-2 mm per year, but varies around the coastline between -1 and +3 mm per year.

High resolution return level estimates for the Severn Estuary and Bristol Channel are provided. Tables of future protection from a given existing design, and tables of structure lifetime failure probability and encounter risk are given.

Use of the report

The results given in this report supersede all previous quoted results in Dixon and Tawn (1994, 1995). If interest is only in final estimates then only the final tables of the report, containing the return levels, in Chapter 8-10, need to be studied. However, the discussion contained in Dixon and Tawn (1994, 1995) provides a deeper understanding of the site-by-site and spatial methods and an appreciation of why we take the statistical approaches adopted, how they work, and the caveats of our approach.

Contents

1 Introduction **21**

1.1 Summary of Stage 1 of the project 22

1.2 Summary of Stage 2 of the project 23

1.3 Outline of the report for Stage 3 24

1.4 Use of estimates in this report 25

2 Description of the numerical model data **27**

2.1 The numerical model data 27

2.2 Comparison with site data 31

2.3 Empirical extreme comparisons 36

3 Errors in site data and modification of past results **41**

3.1 Impact of Correcting the Immingham data 48

4 Tides **55**

4.1 General description 55

4.2 Shoreline distance metric 56

4.3 Primary stations 56

4.4 Hydrodynamic model grid 60

4.5 The difference interpolation scheme 60

4.6 Tests 60

4.7 Spatial mapping of tides 61

5 Trends **65**

5.1 Trends in the numerical model 66

5.2 Trend estimation: mean data 66

5.3 Trend estimation: hourly data 67

5.4 Spatial estimation 69

6 Calibrating the numerical model data **73**
6.1 **Approach I: Raw numerical model** . . . 75
6.2 **Approach II: Data calibration** . . . 78
6.2.1 Calibrating the overlapping data . . . 78
6.2.2 Spatial calibration . . . 85
6.2.3 Fitting the SRJPM . . . 85
6.2.4 Return level estimation . . . 87
6.3 **Approach III: Return level calibration** . . . 93
6.3.1 Return level estimation . . . 97

7 Approach IV: Parameter Calibration **101**
7.1 Interaction functions . . . 103
7.2 GEV parameters . . . 104
7.3 Return levels at the sites . . . 105
7.4 Comparisons of results . . . 120

8 Results: tables and figures **121**
8.1 Relative return level results . . . 123
8.2 The one year return level . . . 136
8.3 Coastal distance of a site . . . 140
8.4 Datum and Trend Adjustment . . . 150
8.4.1 Datum levels . . . 150
8.4.2 Spatially estimating the datum level . . . 151
8.5 Worked Examples . . . 154
8.6 Comparisons with annual maximum data estimates . . . 155

9 Complex coastal regions **161**
9.1 Bristol Channel and Severn Estuary regions . . . 162
9.1.1 Data span selection . . . 162
9.1.2 Data calibration . . . 165
9.2 Relative return level results . . . 173
9.3 Trend estimates in the Severn estuary . . . 178
9.4 ODN conversion factor for the Severn estuary . . . 181
9.5 Comparisons of high-resolution results . . . 183

10 Design levels and encounter risk **185**
10.1 Future protection of existing designs . . . 185
10.2 Risk and long-term design . . . 193
10.2.1 Definitions of design level . . . 193

10.2.2 Encounter Risk 195
10.2.3 Worked example 196

11 Acknowledgements 203

12 References 205

13 Appendix 207

List of Figures

2.1 Map showing the locations of all of the UK A-class gauges. 28

2.2 Information on the spans of available hourly data from each of the 41 sites in this study. 29

2.3 Map showing positions of the data sites (triangle), and the numbered numerical model grid locations. 30

2.4 Time series plot of the surges for the largest storm in 1988, from hour number 2001 to 2400. The solid line represents the numerical model at location 58, and the broken line shows the observed storm at Fishguard. 32

2.5 (a) Kernel density estimates of the surge for Fishguard (solid line),and location 58 using overlapping data only (broken line), and the full grid point data (dashed line). (b) Enlarged tail section of the kernel density estimates. 33

2.6 (a) Kernel density estimates of the surge for Aberdeen (solid line), overlapping grid point data at grid point 9 (broken line), and the full grid point 9 data (dashed line). (b) Enlarged tail section of the kernel density estimates. 35

2.7 The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively. 37

2.8 The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively. 38

2.9 The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively. 39

2.10 The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively. 40

3.1 The nearest numerical model grid point data plotted against site data for Wick to Southend. . . . 43

3.2 The nearest numerical model grid point data plotted against site data for Sheerness to Swansea. . . . 44

3.3 The nearest numerical model grid point data plotted against site data for Mumbles to Islay. . . . 45

3.4 The nearest numerical model grid point data plotted against site data for Tobermory to Wick. . . . 46

3.5 Periods of surge data from Immingham, and its nearest grid point are shown, for 1984. Time corresponds to the hour number in 1984. The solid and broken lines are observational data and numerical model data respectively. . . . 47

3.6 The point process location parameter for the surge, μ, against distance; the site-by-site estimates and the spatial estimate with approximate 95% confidence intervals. The solid line is the corrected estimate, and the broken line is the estimate given in DT2. . . . 49

3.7 The point process scale parameter for the surge, σ against distance; the site-by-site estimates and the spatial estimate with approximate 95% confidence intervals. The solid line is the corrected estimate, and the broken line is the estimate given in DT2. . . . 50

3.8 The point process shape parameter for the surge, k, against distance; the site-by-site estimates and the spatial estimate with approximate 95% confidence intervals. The line $k = 0$ is shown as a guide. The solid line is the corrected estimate, and the broken line is the estimate given in DT2. . . . 51

3.9 Spatial estimate of the 100 year return levels. The cross symbols represent estimates obtained from the SRJPM given in DT2. The estimates are to the datum of mean sea-level at each site. . . . 52

3.10 Spatial estimate of the 1000 year return levels. The cross symbols represent estimates obtained from the SRJPM given in DT2. The estimates are to the datum of mean sea-level at each site. . . . 53

3.11 Spatial estimate of the 10000 year return levels. The cross symbols represent the estimates obtained from the SRJPM given in DT2. The estimates are to the datum of mean sea-level at each site. . . . 54

4.1 Quantiles of the tidal distribution at the sites, and at all distances obtained using the tide interpolation model. The quantiles shown are the 95%, 99% and the 99.9% levels. The + symbols indicate the corresponding quantiles, based on tidal predictions from actual observations, for the data sites. . . . 62

4.2 Comparison of estimates of the 99% tidal quantile at the sites. The crosses represent the difference in the estimated quantile from the site and the unadjusted (nearest) numerical model data, and the site names are the difference between the (nearest grid point) spatial tide estimate and the site tides. The broken lines, given as a guide, are differences of plus and minus 5cm. 63

5.1 MSL trend estimates and 95% confidence intervals for the coastal numerical model data. 66

5.2 The spatial trend estimate for the UK coastline. All data have been used to obtain the trend estimate, including the numerical model data to reduce the variability in the annual mean sea-level data. Humber estuary sites are excluded, for reasons discussed in DT2. The marginal estimates are from sites which have more than 4 years of hourly, mean sea-level or annual maximum data. 70

5.3 The spatial trend estimate for the east coast (solid line) and the estimate obtained in DT2 (broken line). 71

5.4 The spatial trend estimate for the UK coastline. 72

6.1 Port diagrams at the sites for **Approach I**. The bold lines are for **Approach I**. Site values, with 95% confidence intervals, are faint continuous lines, and the east coast estimate is shown as a broken line where available. 76

6.2 Port diagrams at the sites for **Approach I**. The bold lines are for **Approach I**. Site values, with 95% confidence intervals, are faint continuous lines, and the east coast estimate is shown as a broken line where available. 77

6.3 Regression lines obtained from fitting (1) standard linear regression to site data against nearest grid point (solid line), (2) from 91,92,...,99 % estimated quantiles from each location for Wick to Sheerness. (dotted line). (3) Site equals to model reference line (broken line) 82

6.4 Regression lines obtained from fitting (1) standard linear regression to site data against nearest grid point (solid line), (2) from 91,92,...,99 % estimated quantiles from each location for Dover to Ullapool. (dotted line). (3) Site equals to model reference line (broken line) 83

6.5 Regression slope estimates of site data against overlapping numerical model data conditional on a threshold on the numerical model data. 84

6.6 Spatial and site-by-site estimates of the location and scale adjustments. The estimates are obtained by fitting a linear regression to estimated top quantiles for the site and the numerical model data at the nearest grid point to the site. 86

6.7 Estimates of the interaction function, $a()$ in the top tidal band, for three data sets. The continuous line interpolates estimates from the full numerical model data from each grid point. The small faint site names are the estimates obtained from the site data, and the large bold names are the estimates obtained from overlapping data from the grid point nearest the site. 88

6.8 Estimates of the scale parameter for three data sets. The continuous line interpolates estimates from the full numerical model data from each grid point. The small faint site names are the estimates obtained from the site data, and the large bold names are the estimates obtained from overlapping data from the grid point nearest the site. 89

6.9 Estimates of the shape parameter for three data sets. The continuous line interpolates estimates from the full numerical model data from each grid point. The small faint site names are the estimates obtained from the site data, and the large bold names are the estimates obtained from overlapping data from the grid point nearest the site. 90

6.10 Port diagrams at the sites for **Approach II**. The bold lines are for **Approach II**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 91

6.11 Port diagrams at the sites for **Approach II**. The bold lines are for **Approach II**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 92

6.12 Regression fits at each site for the return level adjustment factors. The plots show the difference between site estimated return levels, and nearest grid point return levels plotted against scaled probability, which is -log(-log(1-p))-2. The dots are observed differences and the continuous lines are the fitted linear and quadratic regression lines. 94

6.13 Regression fits at each site for the return level adjustment factors. The plots show the difference between site estimated return levels, and nearest grid point return levels plotted against scaled probability, which is -log(-log(1-p))-2. The dots are observed differences and the continuous lines are the fitted linear and quadratic regression lines. 95

6.14 Spatial estimates of the return level adjustment factors for use in **Approach III**. . . . 96

6.15 Port diagrams at the sites for **Approach III**. The bold lines are for **Approach III**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 98

6.16 Port diagrams at the sites for **Approach III**. The bold lines are for **Approach III**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 99

7.1 Spatial estimate of the shape parameter. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site. 103

7.2 Spatial estimate of the shape parameter adjustment. The solid line is the spatial kernel regression estimate, and the points are the site-estimates. For clarity, the long data sites, which have most influence on smoothing are given as heavy points. 104

7.3 Spatial estimate of the shape parameter given by the broken line and obtained by **Approach IV**. Site estimates are indicated by site abbreviations. 105

7.4 Spatial estimate of the interaction a-function for low, mid and high tides in unscaled form. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site. 108

7.5 Spatial estimate of the unscaled interaction a-function obtained by **Approach IV**: for band 1-low tides, band 5-mid tides, and band 10-high tides. Site estimates are indicated by site abbreviations. 109

7.6 Spatial estimate of the location parameter. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site. 110

7.7 Spatial estimate of the location parameter obtained by **Approach IV**. Site estimates are indicated by site abbreviations. 111

7.8 Spatial estimate of the scale parameter. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site. 112

7.9 Spatial estimate of the scale parameter obtained by **Approach IV**. Site estimates are indicated by site abbreviations. 113

7.10 Spatial estimate of the shape parameter obtained by **Approach IV**. Site estimates are indicated by site abbreviations. 114

7.11 Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 115

7.12 Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 116

7.13 Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 117

7.14 Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available. 118

8.1 Spatial estimate of the 10 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown. 125

8.2 Spatial estimate of the 100 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown. 126

8.3 Spatial estimate of the 1000 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown. 127

8.4 Spatial estimate of the 10000 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown. 128

8.5 Spatial estimate of the difference between the 10 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides. 129

8.6 Spatial estimate of the difference between the 100 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides. 130

8.7 Spatial estimate of the difference between the 1000 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides. 131

8.8 Spatial estimate of the difference between the 10000 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides. 132

8.9 Spatial estimate of the 1 year level. The faint broken line is the estimate obtained using the spatial tides. The site names correspond to estimates given by the JPM applied to site data, and the solid line is the calibrated spatial 1 year estimate. 137

8.10 Enlarged map number 1 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 142

8.11 Enlarged map number 2 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 143

8.12 Enlarged map number 3 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 144

8.13 Enlarged map number 4 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 145

8.14 Enlarged map number 5 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 146

8.15 Enlarged map number 7 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 147

8.16 Enlarged map number 7 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 148

8.17 Enlarged map number 8 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols. 149

8.18 Mean sea-level in 1990 relative to ODN plotted against distance from Wick in km. . . . 151

8.19 One year level plotted against distance. The solid line is the spatial estimate, the broken line is the unadjusted estimate, the solid bars are AMM 95% confidence intervals of the one year level estimate, and the crosses are hourly data site estimates from the JPM. . 157

8.20 100 year return level relative to the 1 year level, plotted against distance. The names and 95% confidence intervals lines are for the annual maximum method, and the solid line is the **Approach IV** spatial estimate. The confidence intervals are those of the 100 year return level and are shown as a guide only. 158

9.1 Map of the Bristol Channel and Severn estuary numerical model data. The plus symbols denote the high resolution numerical model grid locations, the numbers 42 to 59 represent the 36km grid model. The crosses denote the UK data sites. 163

9.2 (a): estimates of the 1 year level from a selection (grid point numbers 39 to 58) of the 36km grid model points calculated using five years of data plotted against the full data. The solid line is the line $y = x$. (b): the difference in the two estimates. 164

9.3 One year level estimated using the raw numerical model data combining the 4km Bristol Channel and the 1.3km Severn Estuary models plotted against coastal distance. 167

9.4 Spatial adjustment to 1 year level due to hourly data 170

9.5 The solid line represents the one year level estimated using the numerical model data, spatially corrected using site data, plotted against coastal distance. The dashed line is the raw numerical model estimate. 171

9.6 The solid line is the one year level as obtained by the spataily adjusted fine grid model and the broken line is the estimate obtained using the coarse model of Chapter 8. . . . 172

9.7 Spatial Trend estimate for the SE and BC 178

9.8 The solid line is the 100 year return level as obtained by the spatialy adjusted fine grid model adjusted to ODN. The dashed line is the estimate to MSL datum. The diamonds are the Coles and Tawn spatial estimates, and the crosses are the AMM estimates, both to ODN. 184

10.1 Example of different future protection. The broken port diagram lines are for 1990 and 2020 for a site with shape parameter 0.3 and trend of 1mm per year. The solid port diagram curves are for a shape parameter of 0.0, with the same trend. 186
10.2 Protection given by designing to the 100 year return level in 1990, for a design in 1 years time. 187
10.3 Protection given by designing to the 100 year return level in 1990, for a design in 5 years time. 188
10.4 Protection given by designing to the 100 year return level in 1990, for a design in 10 years time. 189
10.5 Protection given by designing to the 100 year return level in 1990, for a design in 25 years time. 190
10.6 Protection given by designing to the 100 year return level in 1990, for a design in 50 years time. 191
10.7 Protection given by designing to the 100 year return level in 1990, for a design in 100 years time. 192
10.8 Design level for an encounter risk of 0.99, and a lifetime of 25 years plotted against distance. 197
10.9 Design level for an encounter risk of 0.9, and a lifetime of 25 years plotted against distance. 198
10.10 Design level for an encounter risk of 0.37, and a lifetime of 25 years plotted against distance. 199
10.11 Design level for an encounter risk of 0.99, and a lifetime of 50 years plotted against distance. 200
10.12 Design level for an encounter risk of 0.9, and a lifetime of 50 years plotted against distance. 201
10.13 Design level for an encounter risk of 0.37, and a lifetime of 50 years plotted against distance. 202

List of Tables

4.1 Reference table for locating a site on the distance metric, given its latitude and longitude. 57

4.2 Metric distances of the data sites, and their latitudes and longitudes. ACD is the adjustment that should be applied to our results in later sections, to adjust them from the MSL datum to ACD. The adjustments should be added to MSL to get ACD. 58

4.3 Metric distances of the data sites, and their latitudes and longitudes. ACD is the adjustment that should be applied to our results in later sections, to adjust them from the MSL datum to ACD. The adjustments should be added to MSL to get ACD. 59

5.1 Mean sea-level trend estimates: at the sites, and for the difference between site MSL and numerical model MSL. Ratio gives the ratio of the standard errors for the two methods-with values less than one indicating the numerical model data helps. 68

6.1 Summary of regression model fits at Wick. The parameter σ is an estimate of the variance of the regression error variable, ϵ_t. RSS and TSS are the residual and total sum of squares respectively: these measure the fit of the model, with the ratio of the two R^2 being a measure of fit that corresponds to the percentage of the variation in the model that is explained by the regression terms. Broadly, a value close to or much less than 100% with a small number of regression parameters, corresponds to a very good or poor regression model respectively. 79

7.1 Return level estimates at the data sites, obtained using the site tides in **Approach IV**. Estimates are to ACD. 119

8.1 Return level estimates (in metres), for return periods 10, 25, 50, 100, 250, 500, 1000, and 10000 years, relative to the 1 year level for the east coast. 133

8.2 Return level estimates, in metres, for return periods 10, 25, 50, 100, 250, 500, 1000, and 10000 years, relative to the 1 year level for the south coast. 134
8.3 Return level estimates, in metres, for return periods 10, 25, 50, 100, 250, 500, 1000, and 10000 years, relative to the 1 year level for the west coast. 135
8.4 Estimated 1 year level against the distance metric around the coast, evaluated using the spatial tidal estimate, corrected for the JPM site estimates. 138
8.5 The one year level, in 1990, at the data sites as estimated using the JPM. 139
8.6 Table of the spatial ODN to MSL adjustment in metres, DC(d), for each distance around the coast. 152
8.7 Spatial trend estimate for each distance around the coast. 153
8.8 Estimates of the 10 year return level, in metres, to ODN, for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method. 159
8.9 Estimates of the 10 year return level, in metres to ODN, for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method. 160

9.1 Reference table for locating a site on the distance metric for the SEM and BCM, given its latitude and longitude. 165
9.2 Reference table for locating a site on the distance metric for the SEM and BCM, given its latitude and longitude. 166
9.3 Estimated 1 year level (to MSL) against the distance metric for the Bristol Channel and Severn Estuary. 168
9.4 Estimated 1 year level (to MSL) against the distance metric for the Bristol Channel and Severn Estuary. 169
9.5 Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary. 174
9.6 Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary. 175
9.7 Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary. 176
9.8 Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary. 177

9.9 Estimated trend against the distance metric for the Bristol Channel and Severn Estuary. . . . 179
9.10 Estimated trend against the distance metric for the Bristol Channel and Severn Estuary. . . . 180
9.11 Estimated ODN to MSL adjustment against the distance metric for the Bristol Channel and Severn Estuary. . . . 181
9.12 Estimated ODN to MSL adjustment against the distance metric for the Bristol Channel and Severn Estuary. . . . 182

13.1 East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 1-30. Return levels are given for return periods of 10, 25, 50 and 100 years. . . . 208
13.2 East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 31-60. Return levels are given for return periods of 10, 25, 50 and 100 years. . . . 209
13.3 East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 61-83. Return levels are given for return periods of 10, 25, 50 and 100 years. . . . 210
13.4 Return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 1-30. Return levels are given for return periods of 250, 500, 1000, 10000 years. . . . 211
13.5 East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 31-60. Return levels are given for return periods of 250, 500, 1000, 10000 years. . . . 212
13.6 East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 61-83. Return levels are given for return periods of 250, 500, 1000, 10000 years. . . . 213
13.7 Estimates of the 100 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method. . . . 214
13.8 Estimates of the 100 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method. . . . 215

13.9 Estimates of the 1000 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method. 216
13.10 Estimates of the 1000 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method. 217

Chapter 1

Introduction

This report describes the third of three stages of the MAFF funded project *Estimates of Extreme Sea Conditions*. The broad aims of the overall study are to produce improved statistical methods for the analysis of extreme sea-levels and to systematically apply these to estimate design levels for all coastal sites using the method of analysis which best exploits all the available information. The overall project is broken down into three stages as follows:

Stage 1:

The development, systematic application, and inter-comparison of three methods of extreme sea-level analysis: the r-largest, the Joint Probabilities, and the Revised Joint Probabilities Methods. Each of these methods uses only data from the site of interest so could only be applied for sites with long records. Application was restricted to periods of hourly data from the 22 sites:

Wick, Aberdeen, North Shields, Whitby, Immingham, Cromer, Lowestoft, Felixstowe, Southend, Sheerness, Dover, Newlyn, Ilfracombe, Avonmouth, Milford Haven, Fishguard, Holyhead, Heysham, Portpatrick, Ullapool, Stornoway and Lerwick.

Stage 2:

The extension of the Revised Joint Probabilities Method to incorporate all relevant types of data, such as historical annual maximum still water levels and spatial data from neighbouring sites. This method is applied to data from sites on the UK south and west coasts to give design level estimates on a site-by-site basis, and spatially over a fine regular grid along the UK east coast.

Data sites which are analysed here but were excluded from Stage 1 of the study are:

Leith, Harwich, Walton, Newhaven, Portsmouth, Weymouth, Devonport, Hinkley, Newport, Swansea, Mumbles, Barmouth, Liverpool, Port Erin, Workington, Millport, Islay, Tobermory and Kinlochbervie.

Stage 3:

The spatial methods developed in the second stage of the project are extended to incorporate the additional information contained in a continuous 39 year run of a hydrodynamical model for tides and surges on a 36×36 km grid over the European continental shelf. This method will be used to provide design level estimates over a fine regular grid for the entire mainland UK coastline.

The low-resolution hydrodynamical model data is inadequate for some of the complex coastal regions. Data from a high resolution numerical model is examined for the Seven Estuary and Bristol Channel regions.

Current report:

This current report will generally be self contained, although some reference to the report of the first two stages of the project *Extreme Sea-Levels At The UK A-Class Sites: Site-By-Site Analyses*, and *Extreme Sea-Levels At The UK A-Class Sites: Optimal Site-By-Site Analyses and Spatial Analyses for the East Coast*, referenced as Dixon and Tawn (1994, 1995) respectively will be made. A brief summary of the objectives and findings of Stages 1 and 2 are given in Sections 1.1 and 1.2 respectively, and an overview of this report is given in Section 1.3.

1.1 Summary of Stage 1 of the project

The objectives of the first stage of the work were:

- To describe in detail the existing statistical methodology for the site-by-site techniques and to compare these methods. These were given in Sections 4 and 5.
- Based on the wide experience gained through systematic application of the existing methods to a range of data sites, where the sea-level processes exhibit a variety of physical characteristics, to refine these methods so that they have better properties and more extensive applicability. These refinements were described in Section 6.
- To obtain the first systematically derived set of return level estimates, with associated measures of precision, at each A-class site for which site-by-site methods give reliable estimates. Such results, displayed in both graphical and tabular form, were given for each site in Sections 7 and 8.
- To develop substantive new methodology for the analysis of extreme sea-levels in the form of Joint Probability Methods for still water levels and waves. These were detailed in Section 9 of the report.

The principal findings obtained in that study were:

- At sites where the surge has a large variability at high tidal levels relative to the variability between high tides, then the r-largest, Joint Probability Method and Revised Joint

Probability Methods each give broadly similar results. Generally, this is the case for sites in the South-East of the UK.

- At sites where the variability of high tides is large relative to the variability of the surge at high tidal levels, then both the annual maxima and r-largest methods under-estimate return levels, that is the methods over-estimate the return period of observed levels. Generally this is the case for sites on the UK west coast. The degree of under-estimation is reduced as the length of the annual maxima record is increased, but in some cases data from many nodal cycles of the tide are required before the bias is adequately reduced.

- Trends in extreme sea-level data were estimated, but the estimates are highly variable owing to the short periods of hourly observations, and the use of only extreme value data in the estimation of trends.

- The Joint Probability and Revised Joint Probability Methods provide accurate estimates from much shorter series than the r-largest method.

- Of the Joint Probability and Revised Joint Probability Methods, the latter is the better provided there are at least 5-10 years of hourly observation.

In general the recommendation was that the best estimates of return levels, based on the site-by-site methods, are given by the Revised Joint Probability Method provided that sufficient high quality hourly data are available.

1.2 Summary of Stage 2 of the project

Data from 41 sites were considered in this stage of the project. Dixon and Tawn (1994) found that the three site-by-site methods only produced reliable statistical results for 22 of these 41 sites. By better handling of trends in the statistical analysis, use of historical annual data, and the exploitation of spatial coherence of the extreme sea-level process through a spatial statistical analysis, results for the other 19 sites were obtained and improvements made to estimates for the original 22 sites. Furthermore, by use of the spatial model developed for the report, estimates of extreme still water levels were given for sites at regular intervals along the UK east coast for which data are non-existent.

The work was subdivided into four steps, related to the four parts of the report:

Part I:

- A substantial extension of the Revised Joint Probability Method as used by Dixon and Tawn (1994) to include all types of relevant available data from the site and such that the parameters of the model have a clear spatial interpretation. The new method was called the Spatial Revised Joint Probability Method.

Part II:

- Obtaining design estimates, in the form of return levels and trend estimates for all 41 sites in the study based on data from the site of interest only, including the 19 sites which were not studied by Dixon and Tawn (1994).
- For each site the results from the best method of analysis were given.

Part III:

- The development of a spatial model for extreme sea-levels.
- Many case-studies are given to aid the development of the spatial extension of the model in Part I.

Part IV:

- The application of the spatial model along the UK east coast.
- Return level and trend estimates are given for a regular grid along the east coast.
- For A-class data sites on the east coast, comparisons of the spatial estimates were made with the best estimates from the analysis of data for the individual sites.

1.3 Outline of the report for Stage 3

The following gives a brief summary of the contents of each chapter of this report for Stage 3.

- The numerical model data is described in Chapter 2. In Section 2.2 we compare the model data with observational data from the 41 A-class sites.
- One use of the numerical model is to locate erroneous site data. In Chapter 3 we examine how this can be done and locate hitherto undetected erroneous site data. The impact of using the corrected observational data is examined by repeating the spatial analysis of Stage 2.
- In Chapter 4 the use of the numerical model for trend estimation is considered. A spatial trend estimate for the UK coastline is obtained.
- In Chapter 5 we describe how the numerical model is used to obtain tides at every point around the coastline.
- Chapter 6 presents the development and application of three approaches aimed at incorporating the numerical model data. These include use of the raw numerical model data, use of calibrated data, and calibration of return level estimates from the raw model data.

- In Chapter 7 our preferred approach is developed. This incorporates the numerical model data by calibrating the key parameter estimates for the SRJPM using these data. The resulting estimates are shown to capture characteristics of site-by-site estimates better than the other methods.

- Chapter 8 presents return level estimates for a regular grid around the UK coastline. Here it is shown that the mapping of the tides is particularly important and highly influences the statistical interpolation of return levels. By considering the differences between the return level estimates and the one year return level estimate, we are able to present the statistical information about extrapolation excluding the tides. We also present the one year return level based on our analysis, although this aspect can be substantially improved by using short records at the site of interest.

- Chapter 9 describes the development of methods to incorporate high resolution numerical model data in order to more reliably estimate return levels in complex coastal regions. Results for the Severn estuary and Bristol Channel are given.

- Chapter 10 gives an assessment of risk in terms of protection offered by existing structure designs, and an assessment of encounter risk, i.e. the design height required for an acceptable structure lifetime failure probability.

1.4 Use of estimates in this report

The estimates in this report have been produced in a systematic and consistent fashion for each point along the coast using the best currently available statistical methods. The methods are only able to extract information from the available data, so that even though a large database of sea-level elevations augmented with historical and numerical model data is used, the resulting return level and trend estimates may be inaccurate if the available data are biased. In addition, the spatial method only provides improved estimates over marginal analyses if our assumption of spatial coherence is valid at the site under consideration. In most cases the data are representative, and the coherence assumption is valid. However, careful analysis carried out by an experienced coastal engineer who is able to use additional knowledge of the site or additional historical or other data which has not been used in this study may provide improved estimates at a particular site. The spatial estimates are generally least reliable when applied to sites in bays and inlets. Generally the estimates given here are recommended but should be used as a guide rather than a standard.

Finally, estimates given in Chapter 8, for complex shaped coastal regions, such as the Humber estuary, the Wash, the Southern North Sea, the Thames estuary, the Solent, and Morecambe

Bay, should be treated with caution unless a good estimate of the one year level is available (such as can be obtained from at least one year of data from the site.)

Chapter 2

Description of the numerical model data

The aim of this stage of the project is to develop a spatial model for the entire coastline so that estimates of extreme sea-levels can be given for any coastal position and not just at the data sites. In Dixon and Tawn (1995), subsequently referred to as DT2, it was only possible to do this for the east coast of the UK. This is because on other coastlines the data sites provide insufficient coverage to accurately determine the behaviour at any location. This is evident from Figures 2.1 and 2.2 where it can be seen that although the spatial density of sites is reasonably high, most sites along these coasts have short records.

The idea here is to exploit information from a hydrodynamical model, referred to subsequently as the numerical model, to provide extra information for spatial interpolation. In addition the numerical model provides increased temporal information, since it contains data from a common time span along the whole coastline which is longer in duration than all sites except for Newlyn. In this chapter we describe the numerical model data, and present some preliminary analyses.

2.1 The numerical model data

The numerical model data consist of synthetic hourly sea-levels, with corresponding tidal and surge levels for 39 years between 1955 and 1993. The data are available at 2964 locations on a regular grid of resolution 36×36 km over the North-West European Continental Shelf. The model uses meteorological data to generate the synthetic surge data. The tides are generated by physical laws. We use a subset of the data, namely the data at each of 89 grid points that are nearest to the UK coastline. The numbers from 1 to 89 displayed on Figure 2.3 show the grid locations used. The data sites are shown on the figure as triangles, illustrating the poor

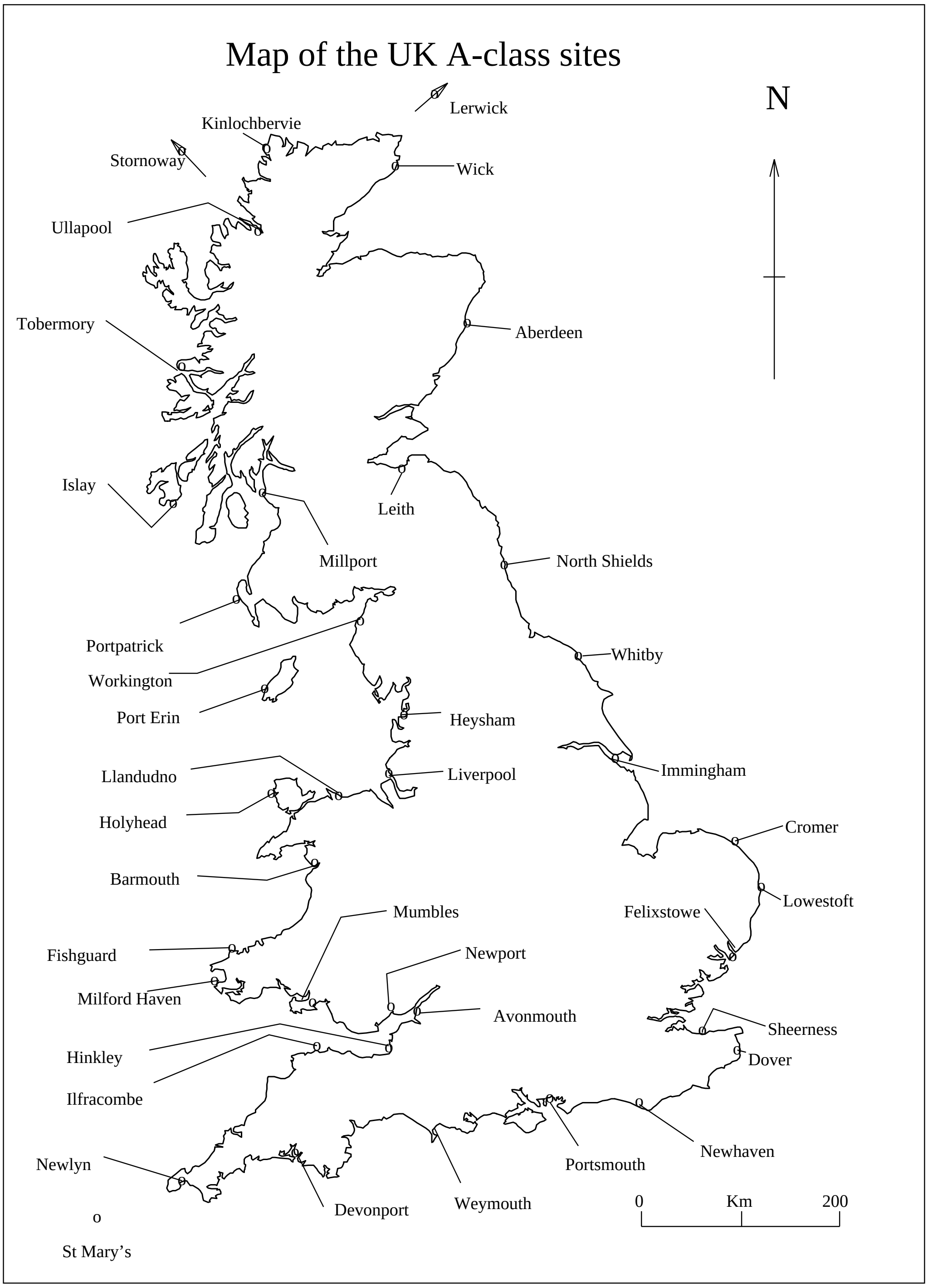

Figure 2.1: Map showing the locations of all of the UK A-class gauges.

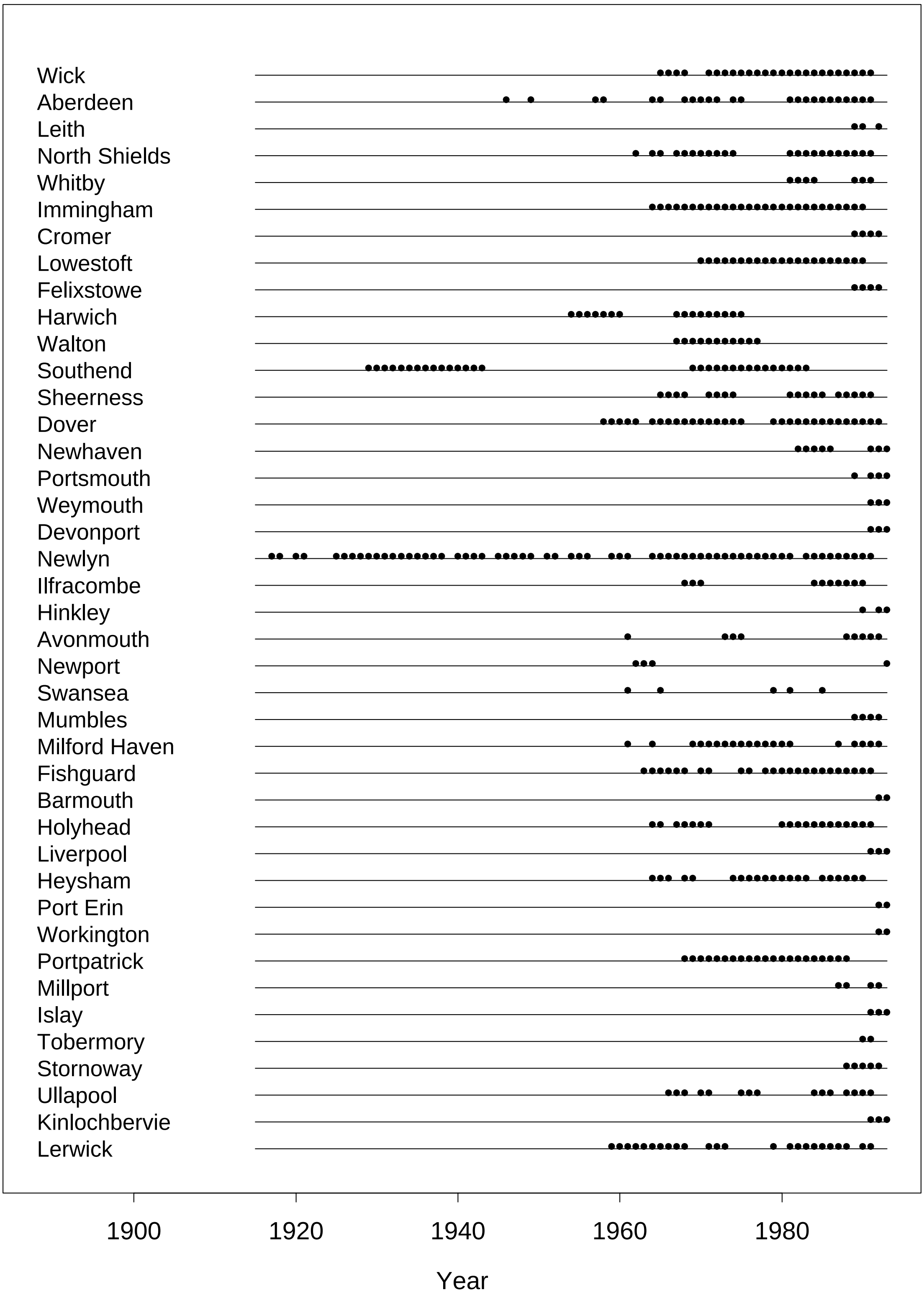

Figure 2.2: Information on the spans of available hourly data from each of the 41 sites in this study.

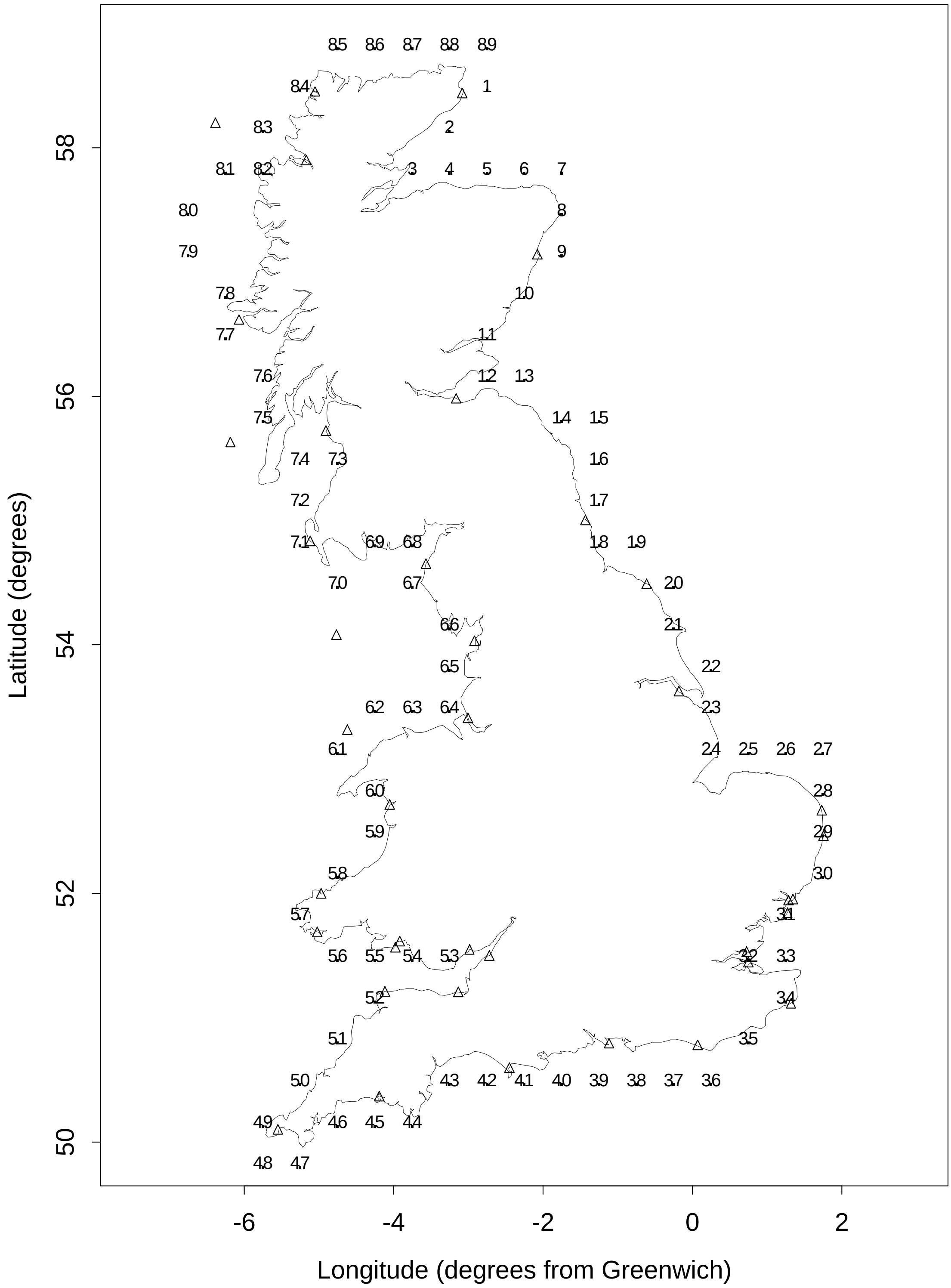

Figure 2.3: Map showing positions of the data sites (triangle), and the numbered numerical model grid locations.

coverage of observational sites relative to model data sites.

We consider estimation of the tide and surge separately and recombine estimates in later stages. The tidal estimation, discussed Chapter 4, is handled in a similar way to tides for the east coast in DT2, with only minor modifications to incorporate the finer spatial structure of the south and west coastlines. The aim in the first part of the report is to use the numerical model data to improve estimation of the surge: thus we only examine the numerical model surge data in the following sections.

2.2 Comparison with site data

Comparisons of the site data with the numerical model data are affected by several aspects of the sea-level process such as local bathymetry, the shape of the neighbouring coastline and the distance of the grid point to the coastline. In general, the coastline has a complex shape, and the grid points vary in distance from the coast and other data sites. As can be seen from Figure 2.3, most numerical model grid points lie some way from the coastline; usually between 0 and 50km from the shore. These physical features should change gradually along a coastline. To begin investigations, we concentrate on one particular site, namely Fishguard on the west coast, and examine the behaviour of the numerical model at the nearest grid point to the site (grid number 58). Figure 2.4 shows a sample of the time series for the hourly surge process for both Fishguard and grid point number 58. It can be seen that there is generally high correlation between the two series, which suggests that information from the numerical model should be useful in the subsequent analyses. In addition, the numerical model seems to reproduce the main features of the large storm around $t = 100$. More important is how well the numerical model captures the surge distribution; at this stage we compare the empirically estimated surge distribution using the site and the numerical model data. Figure 2.5(a) shows the kernel density estimate of the surge distribution using three different data sets:

- the site data alone for Fishguard
- the full 39 years of numerical model data at grid point 58
- the data from grid point 58 but only values for which concurrent values are available for Fishguard.

For most data sites there is more numerical model data than observed data. For example Fishguard has 24 years of data between 1963 and 1991, and grid point 58 has the continuous 39 years from 1955 to 1993. Throughout the report we make comparisons of the site and numerical model data by using the three types of data listed above. For convenience, the notation for labelling such data sets will be *site-data*, *full grid point data*, and *overlapping grid point data at*

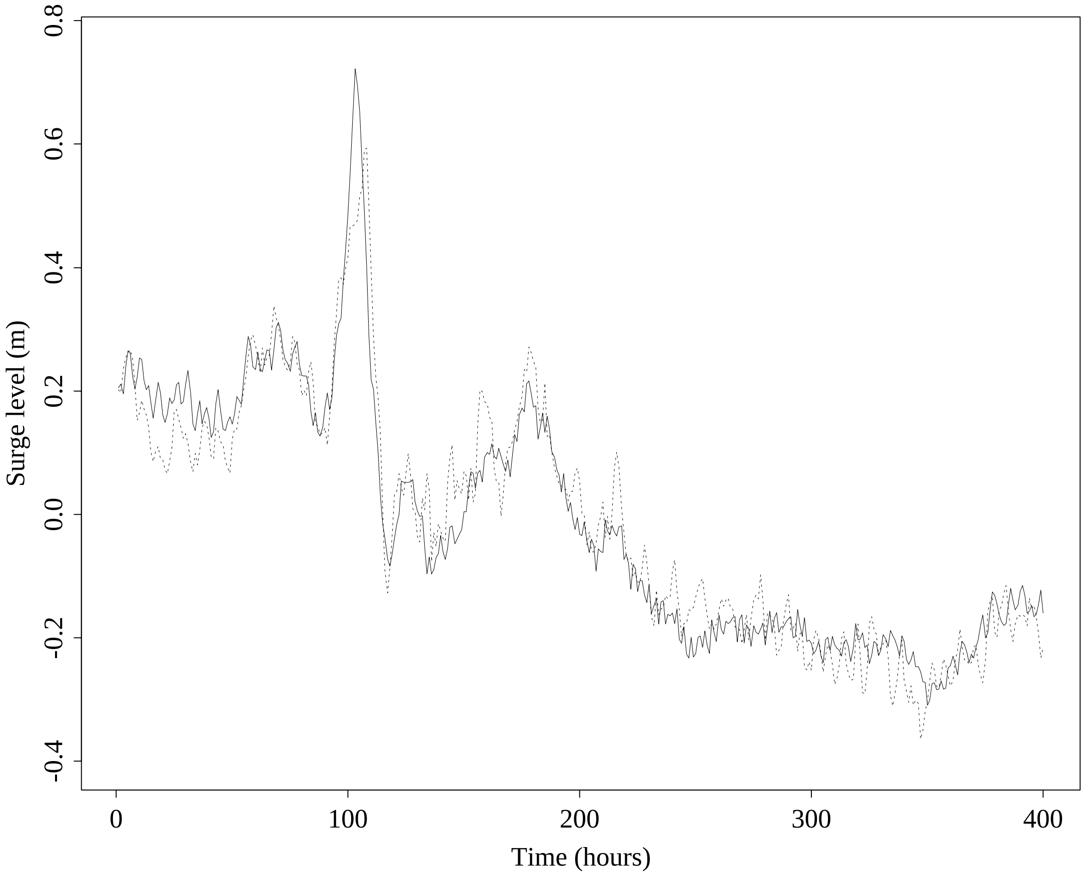

Figure 2.4: Time series plot of the surges for the largest storm in 1988, from hour number 2001 to 2400. The solid line represents the numerical model at location 58, and the broken line shows the observed storm at Fishguard.

the site for the three types respectively. The purpose of examining features for these three data types is to examine

1. how the numerical model data compares with the data on the coastline and
2. how representative the overlapping sample (i.e. the observational data) is for the location under consideration.

There are three possible conclusions that may be drawn from these plots depending on how the curves compare.

1. All three curves are approximately the same. In this case the numerical model data represents the site data well and the sampling period of the site data is not atypical.
2. The two numerical model curves are the same, but differ from the site curve. In this case the numerical model does not represent the site data well, and some form of adjustments

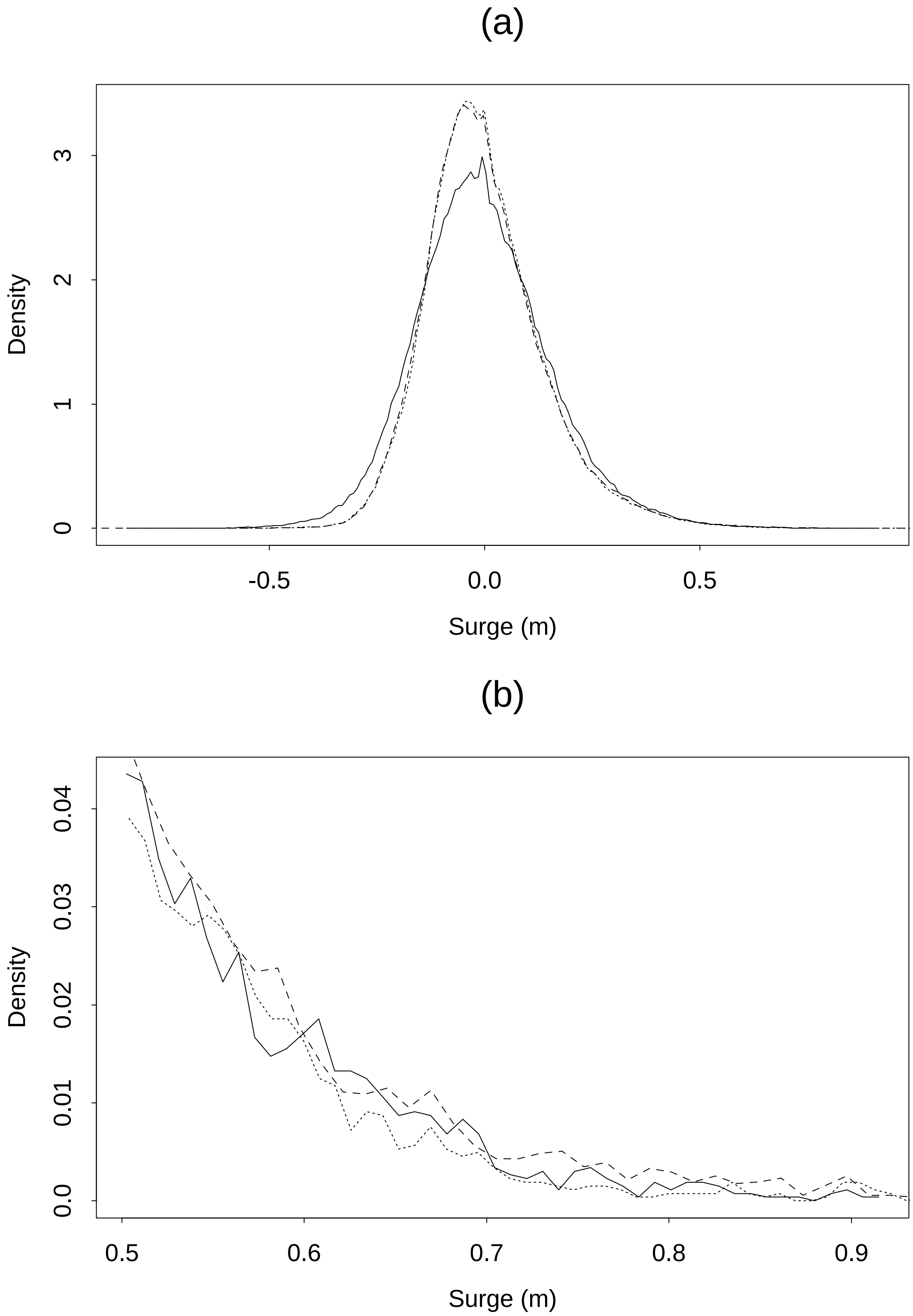

Figure 2.5: (a) Kernel density estimates of the surge for Fishguard (solid line),and location 58 using overlapping data only (broken line), and the full grid point data (dashed line). (b) Enlarged tail section of the kernel density estimates.

are needed if the numerical model data is to be used for return level estimation. However, the observed period of site data is representative of surges over a longer time scale.

3. The overlapping grid point data estimate and the site estimate are the same but differ from the full grid point data estimate. This case is the most interesting. Here, the numerical model data is representing the site well, but the sampling period of the site data is unrepresentative, and biased.

For this example, Figure 2.5(a) suggests that the numerical model represents the distribution at the site fairly well, with perhaps a slight underestimation of the spread. Also, the numerical model overlapping data estimate gives a similar estimate to the full data which suggests that the sampling period for Fishguard is not atypical.

For the purposes of estimation of extreme sea-level probabilities, a more important comparison is the extreme surge density estimates. Thus Figure 2.5(b) displays the tail estimates of the kernel density estimates and shows that there is little difference in the extreme tail of the marginal surge estimates, suggesting that the numerical model provides directly useful information about extreme levels at the site. Similar plots for other sites and their respective nearest grid points shows that this is not always the case and that the numerical model often underestimates the probabilities of extreme events. For example Figure 2.6 shows kernel density estimates using data from Aberdeen and grid point 9. In this case the upper tail of the density seems to be mis-estimated by the numerical model data. It is likely that other grid points near to Aberdeen are underestimating the tail probabilities for the coastline in a similar way to that at Aberdeen. The aim of Chapters 2, 5, 6, and 7 is to quantify the nature of this mis-estimation, and make suitable adjustments so that estimates of the sea-level distribution from the numerical model data represent the true distributions along the coastline. The estimates thus obtained can be used to provide spatial estimates along the coastline. This is the main use of the numerical model data. However, other useful information contained in the model data includes;

- it can be used to help detect erroneous site data
- it can be used to help in estimating the trend along a coastline.

In the next chapter we show how the numerical model data can be used directly as an aid to locating erroneous data at the data sites: in Chapter 3 we show which sites have previously undetected errors, and show the impact of including these erroneous data by re-running some results from Stage 2 of the project. In Chapter 5 we discuss how numerical model data can be used to improve trend estimation, and a spatial estimate of the trend is obtained for the whole coastline.

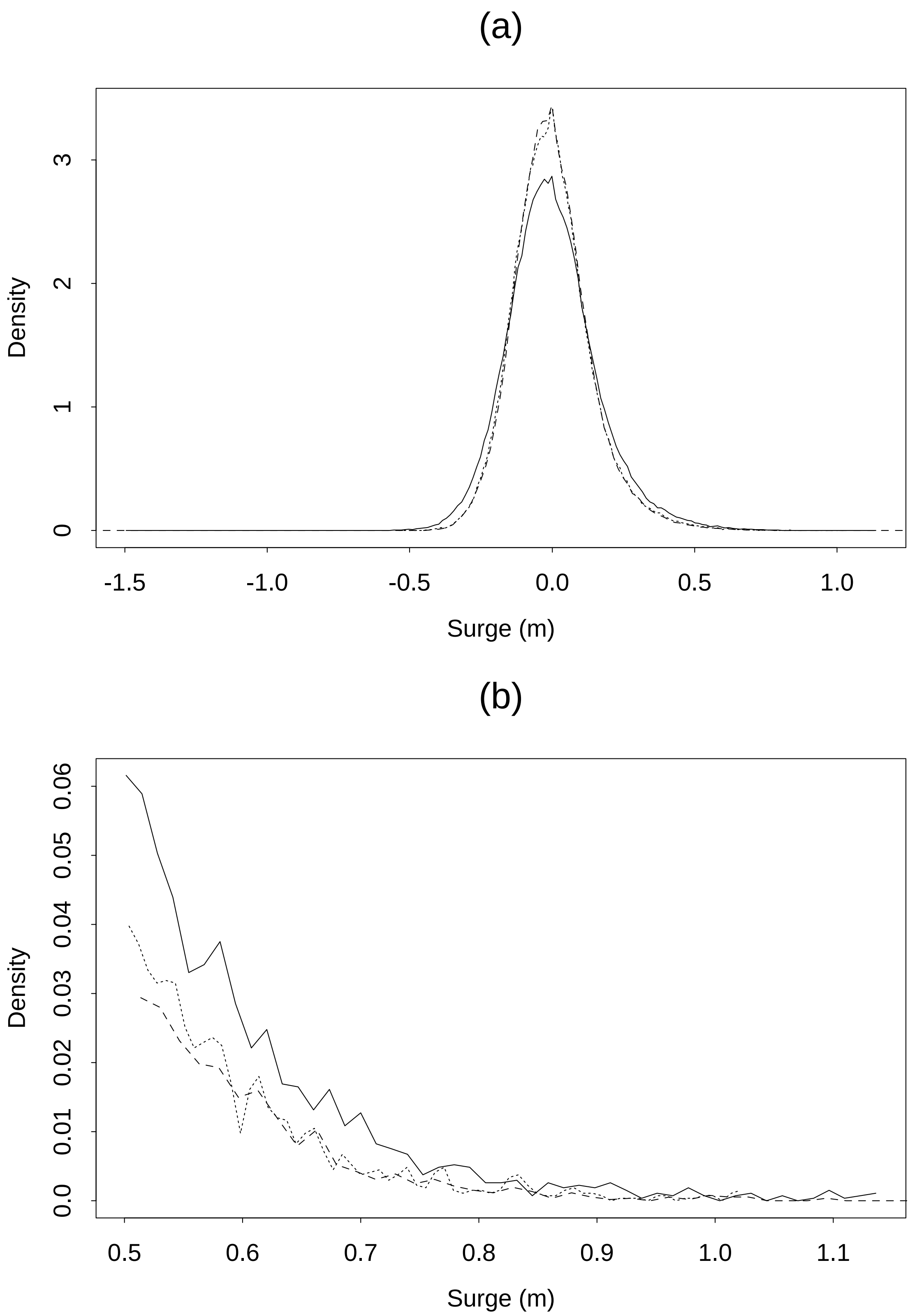

Figure 2.6: (a) Kernel density estimates of the surge for Aberdeen (solid line), overlapping grid point data at grid point 9 (broken line), and the full grid point 9 data (dashed line). (b) Enlarged tail section of the kernel density estimates.

2.3 Empirical extreme comparisons

In this analysis, we are interested specifically in extremes of the sea-level process. As a further investigation into how the extremes of the numerical model data compare to the data at a nearest site, we can examine the annual maximum surge levels at the site and the corresponding annual maxima at its nearest grid point. Figures 2.7–2.10 show the annual maximum surge plotted against year for a selection of sites with long records.

Also shown in these figures is an empirical measure of dependence. Since correlation is an inappropriate measure for dependence in extremes, the plots show an empirical estimate of a dependence function (see Coles and Tawn, 1994). Complete dependence between the variables corresponds to a peak at 0.5 in the histograms, whilst independence corresponds to two peaks, one at each end, i.e. at 0 and 1, of the histograms. Shapes in between these two extremes correspond to

- a strong dependence when the histogram is peaked around 0.5.
- weak dependence when the histogram is uniform or bimodal with modes near 0 and 1.

It is encouraging to see that there is a general pattern of fairly strong dependence, and this suggests that the numerical model data will indeed be useful for aiding extreme sea-level estimation. Also note that these plots only show the *dependence* between model and site data. For example, if the model systematically differs by a certain amount from the site data, such as appears to be the case at Newlyn in Figure 2.9, then there will be high dependence between the two and the numerical model data will provide useful information, although it may need some form of adjustment. Evaluating the required form of adjustment is the theme of Chapters 6 and 7.

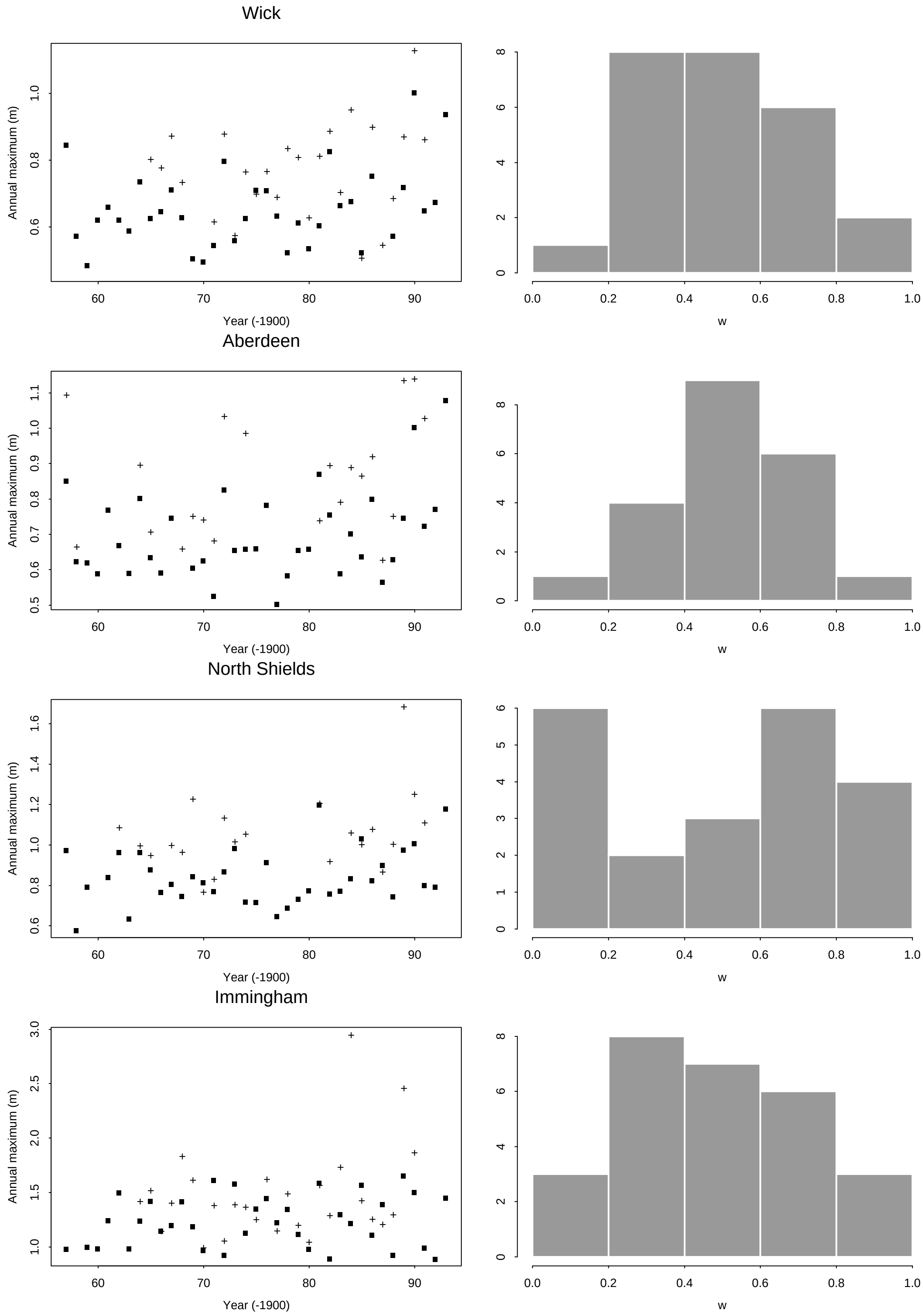

Figure 2.7: The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively.

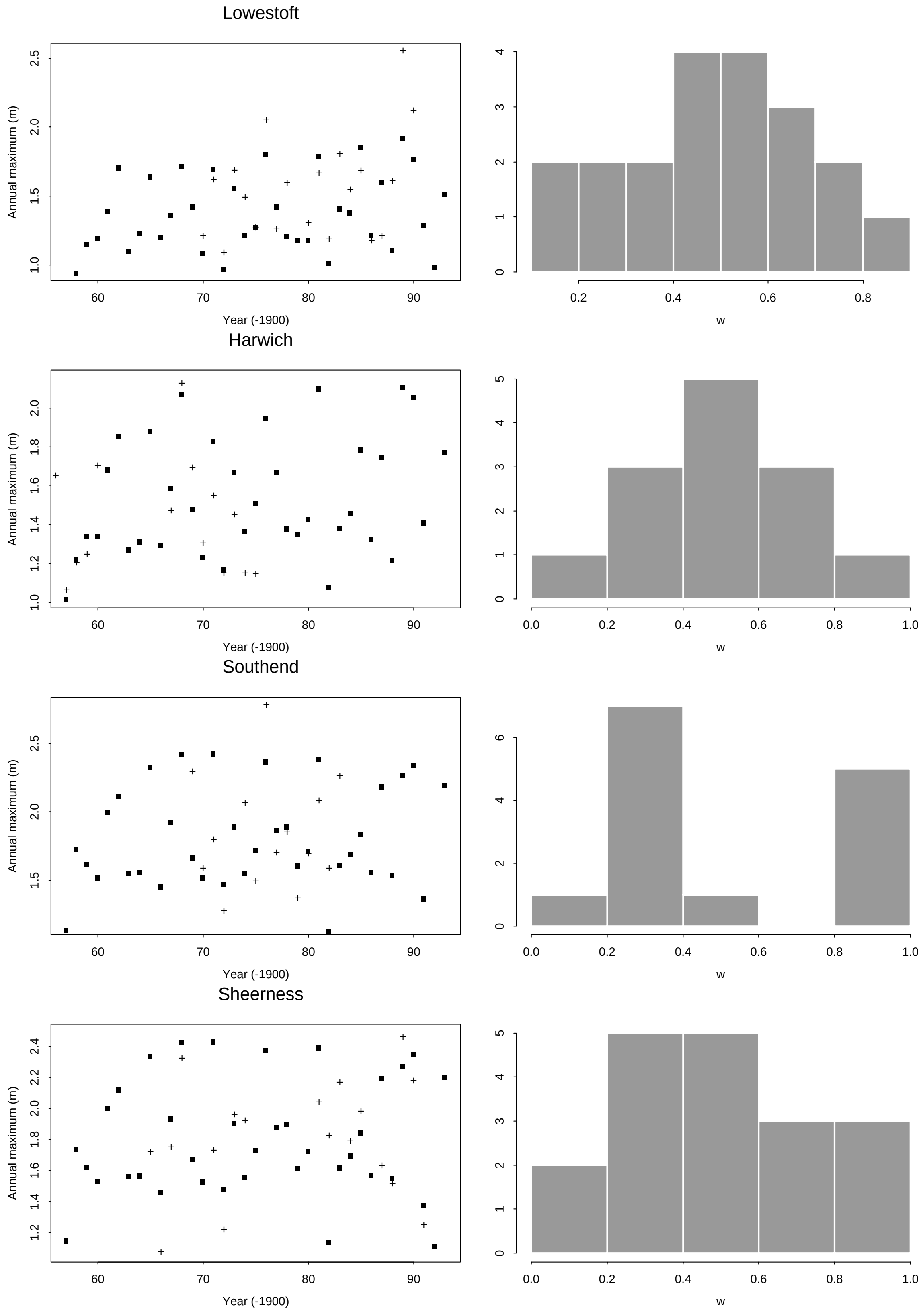

Figure 2.8: The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively.

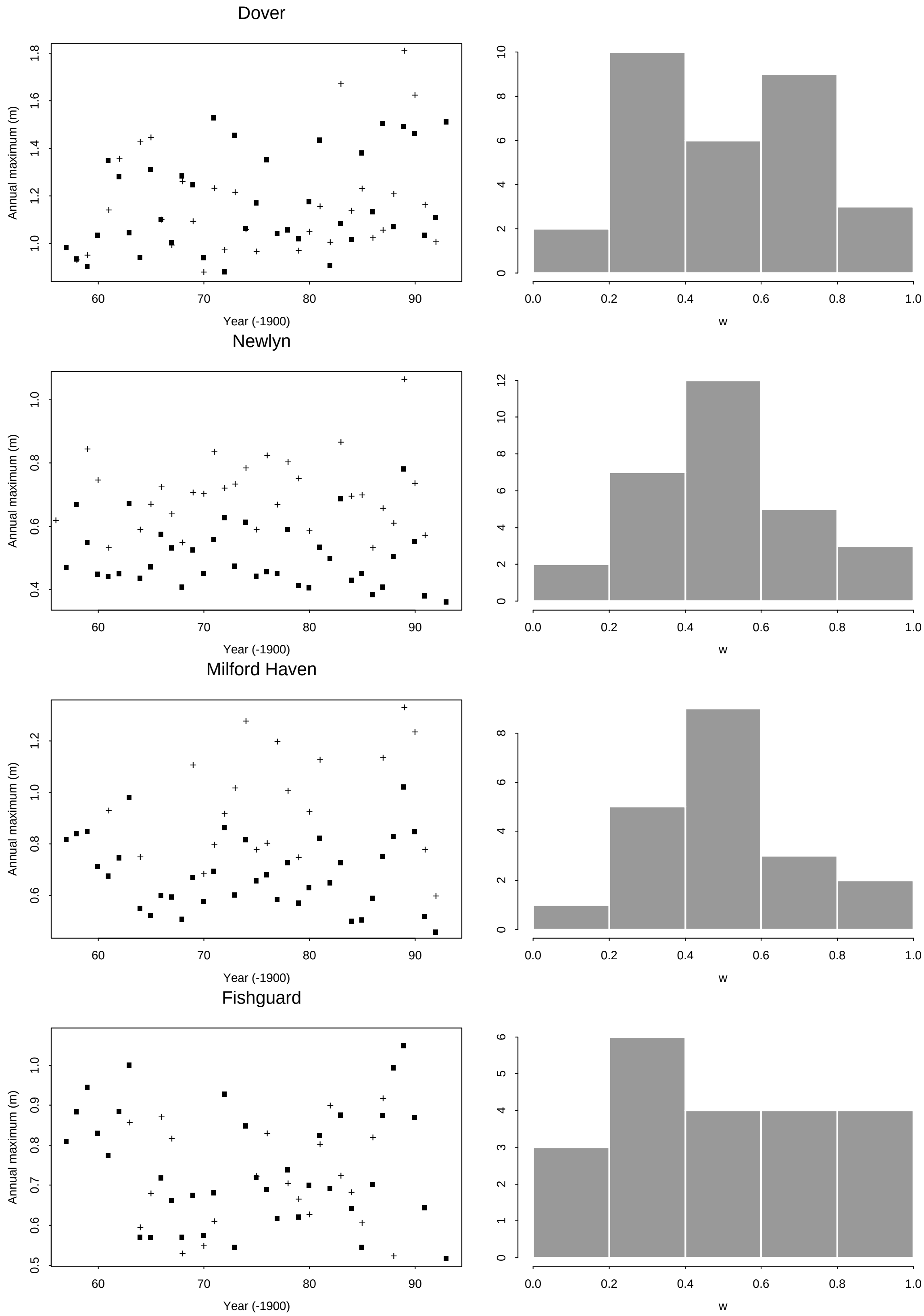

Figure 2.9: The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively.

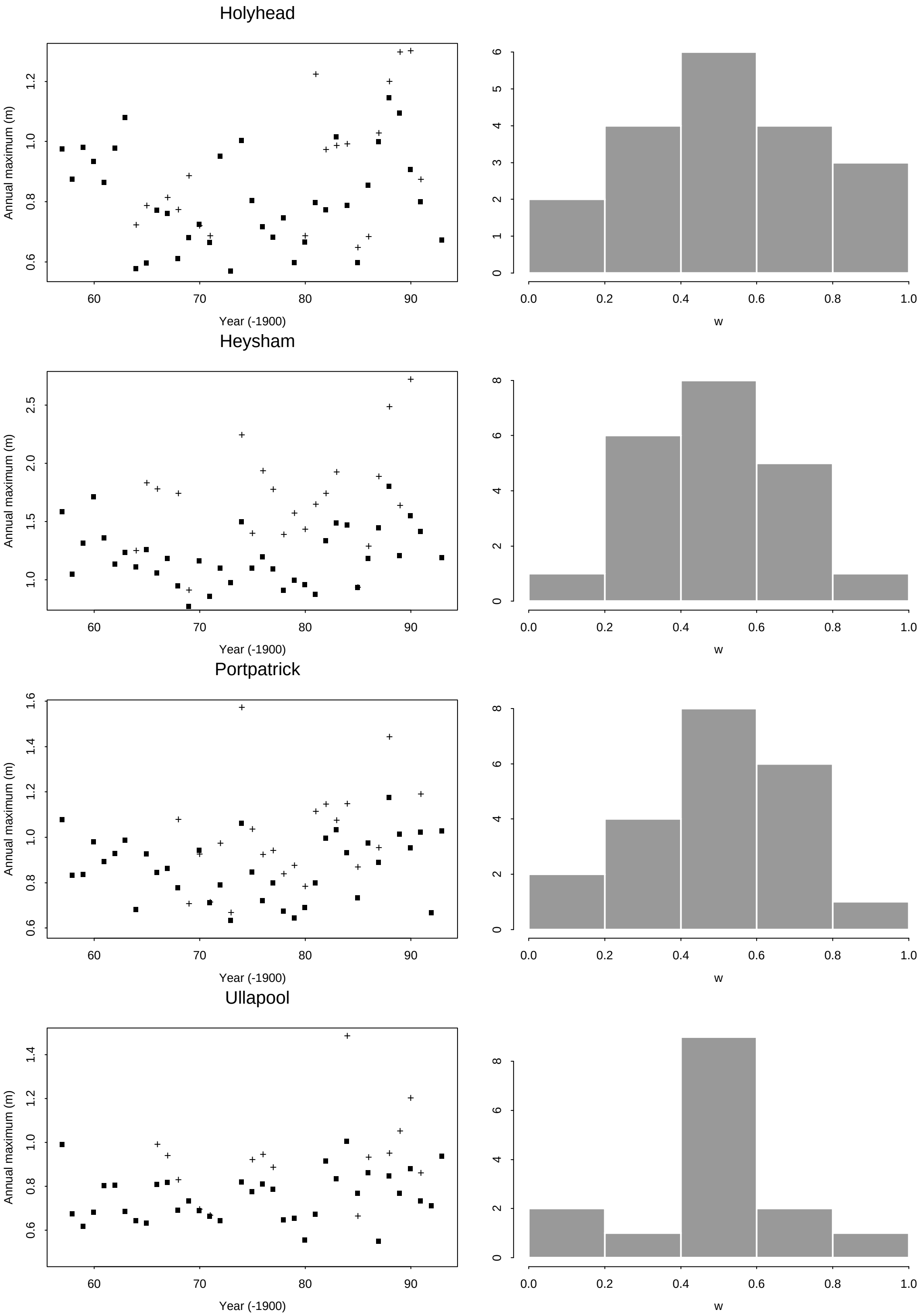

Figure 2.10: The left hand column of figures are plots of the annual maximum surge data for the site and the nearest numerical model grid point. The right hand figures are the dependence histograms. Here the boxes and crosses are numerical model and observational site data respectively.

Chapter 3

Errors in site data and modification of past results

The still water level data has been screened for errors by POL, before being stored by BODC, and then by Dixon and Tawn (1994), subsequently referred to as DT1, prior to the analyses. They plotted the surge series against time on a month by month basis for each site. Since problems with the tide gauge malfunctioning or timing errors typically lead to spurious large positive or negative surges, examination of these plots enables erroneous data to be identified. The existing procedures do not detect all poor quality data, and in this section, we describe one important use of the numerical model; as an additional data quality check. Figures 3.1–3.4 show, for each site, the numerical surge data plotted against the corresponding observed model surge from the nearest grid point to the site. Large differences in the two could be due to an error in the site data. Note that we have only plotted large values of the observed surge data since it is errors in these values that are important from the point of view of estimating extreme high surges. By detailed examination of the time series around these times where the two differ (bottom right of each plot), further errors in the observed data can be detected.

The largest discrepancy is evident at Immingham. Figure 3.5 shows an example of how Figures 3.1–3.4 can be used to highlight erroneous data at a site. Periods of surge data from Immingham, and its nearest grid point are shown, for 1984. The periods shown correspond to all the points in the lower right corner of the Immingham plot in Figure 3.1. These errors were previously undetected, and can severely distort the spatial estimates obtained for the east coast in DT2. By plotting data in this way for all sites that appear to have errors, from examination of Figures 3.1–3.4, the A-class data set can be cleaned up significantly. Although new errors were detected, most were erroneous *low* surges, which have little effect on high period return level estimates. The only sites which had erroneous high surges were Immingham, Aberdeen, and Weymouth. Of these, only the errors at Immingham made a significant impact to the return level estimates.

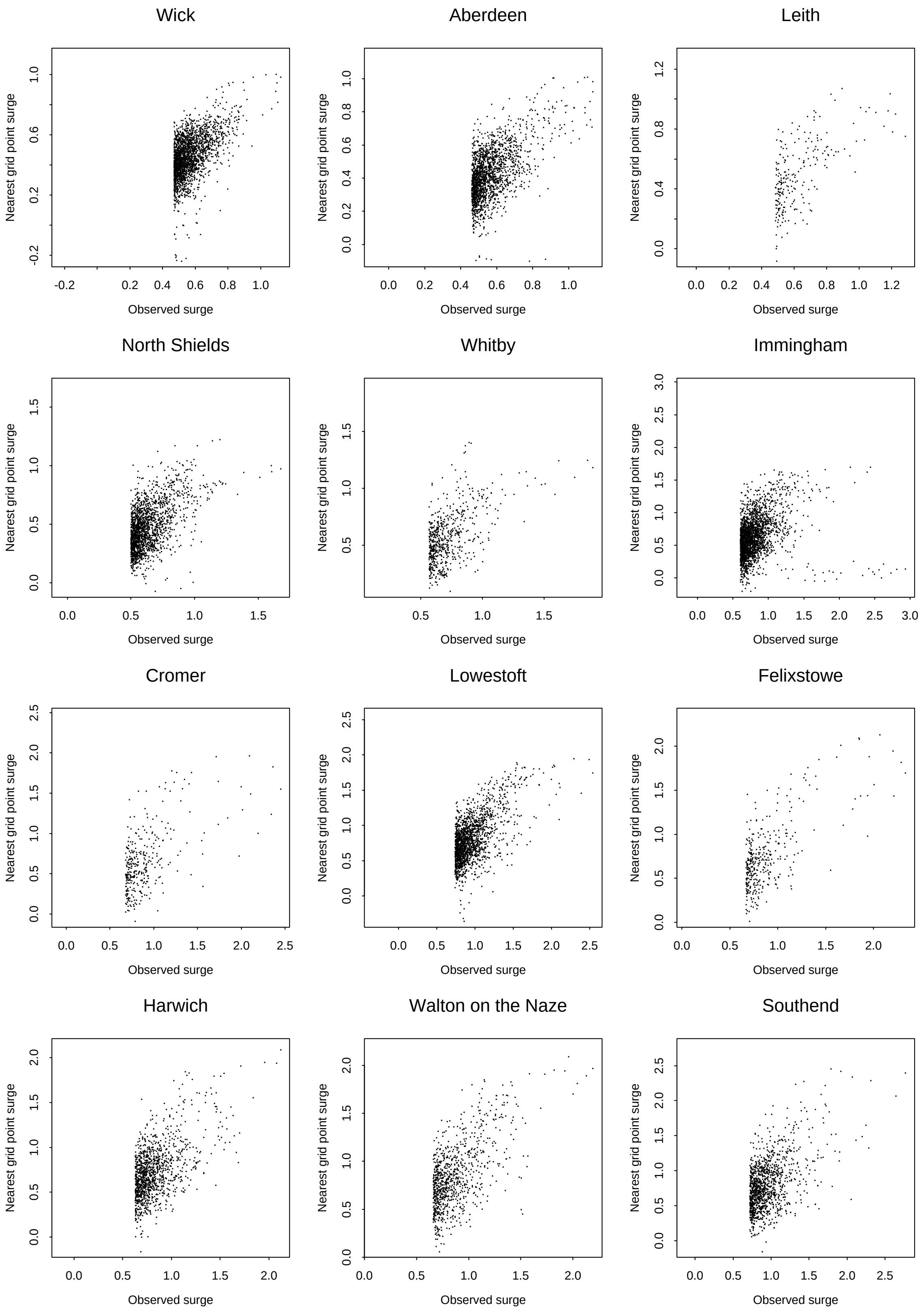

Figure 3.1: The nearest numerical model grid point data plotted against site data for Wick to Southend.

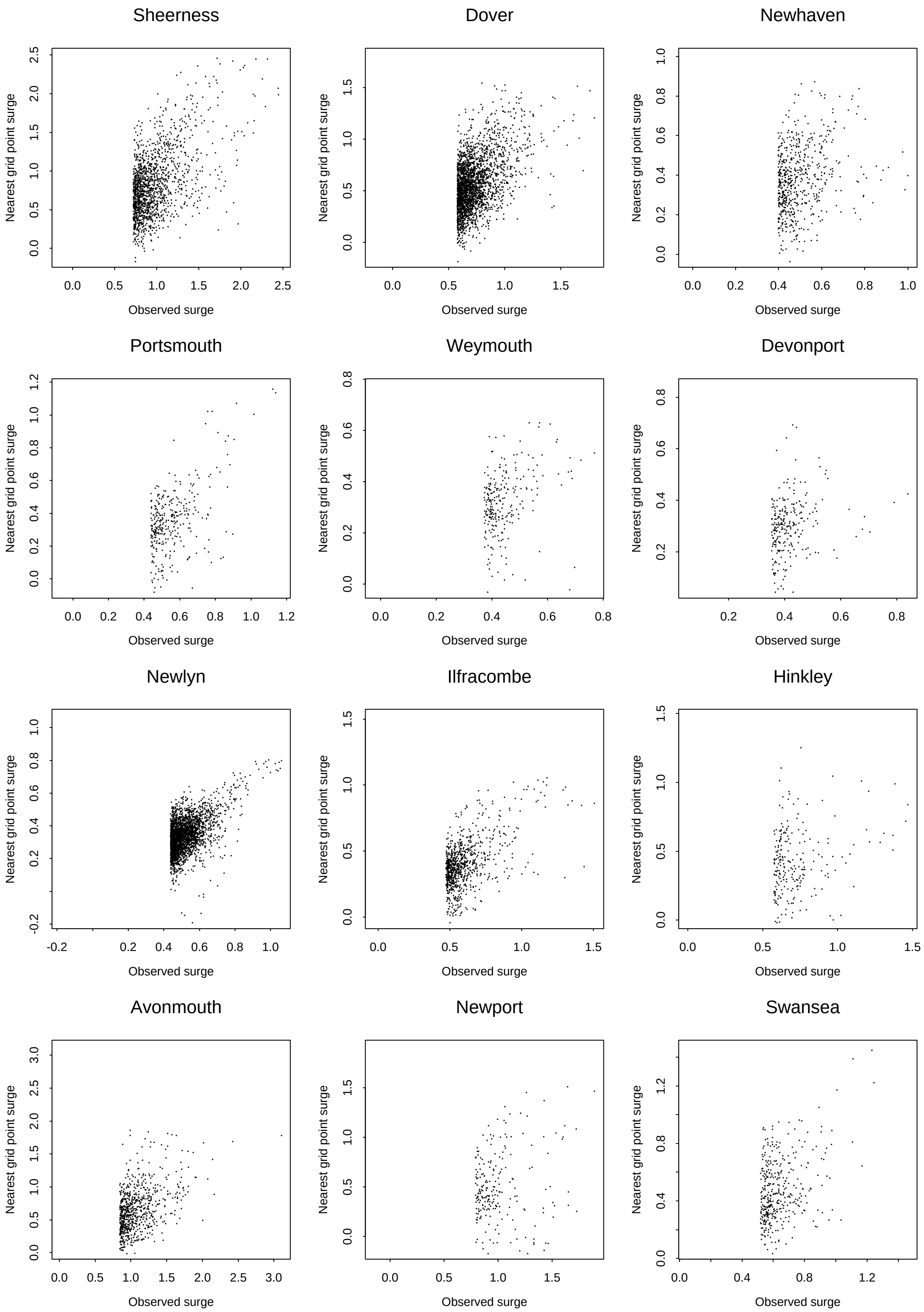

Figure 3.2: The nearest numerical model grid point data plotted against site data for Sheerness to Swansea.

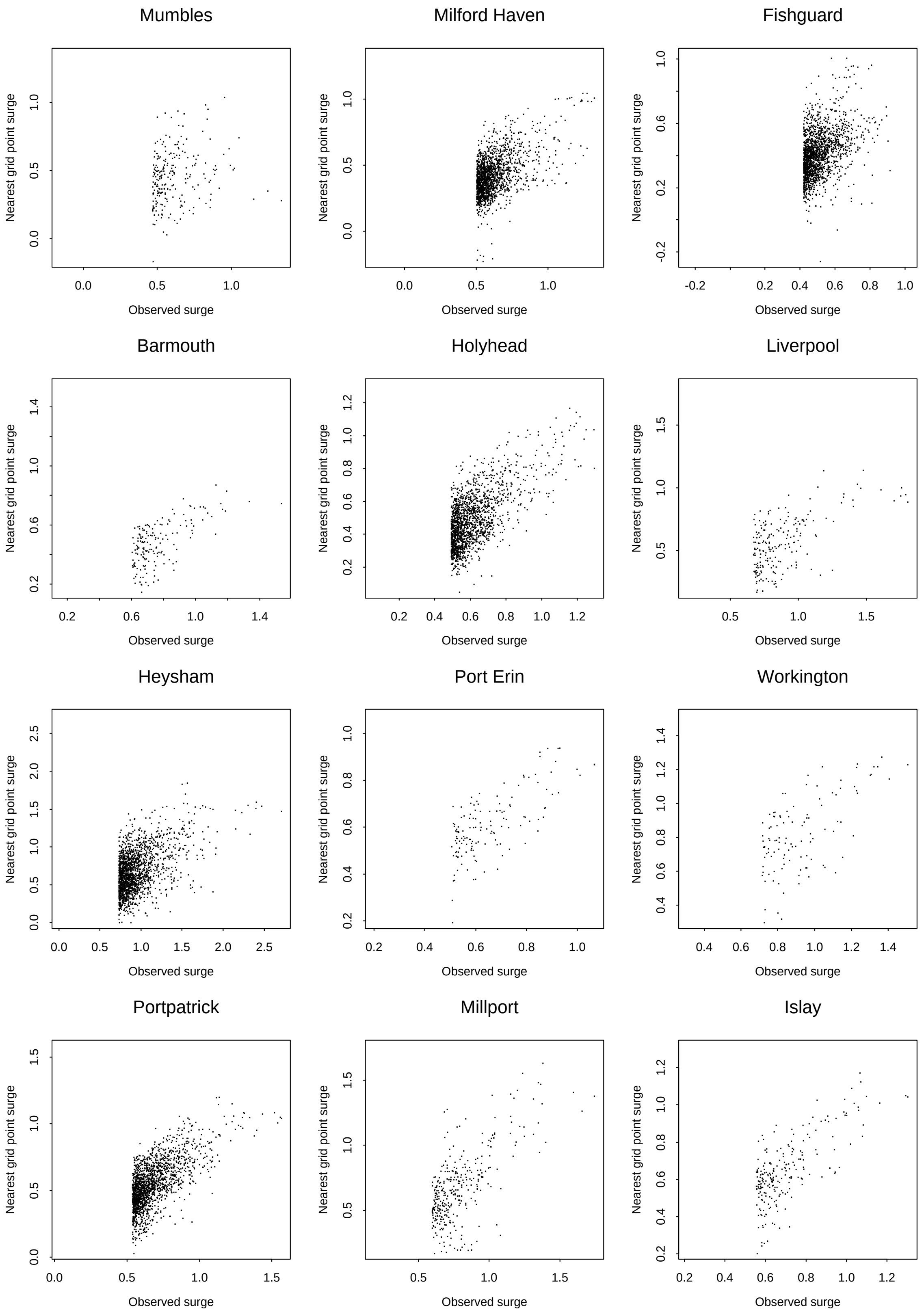

Figure 3.3: The nearest numerical model grid point data plotted against site data for Mumbles to Islay.

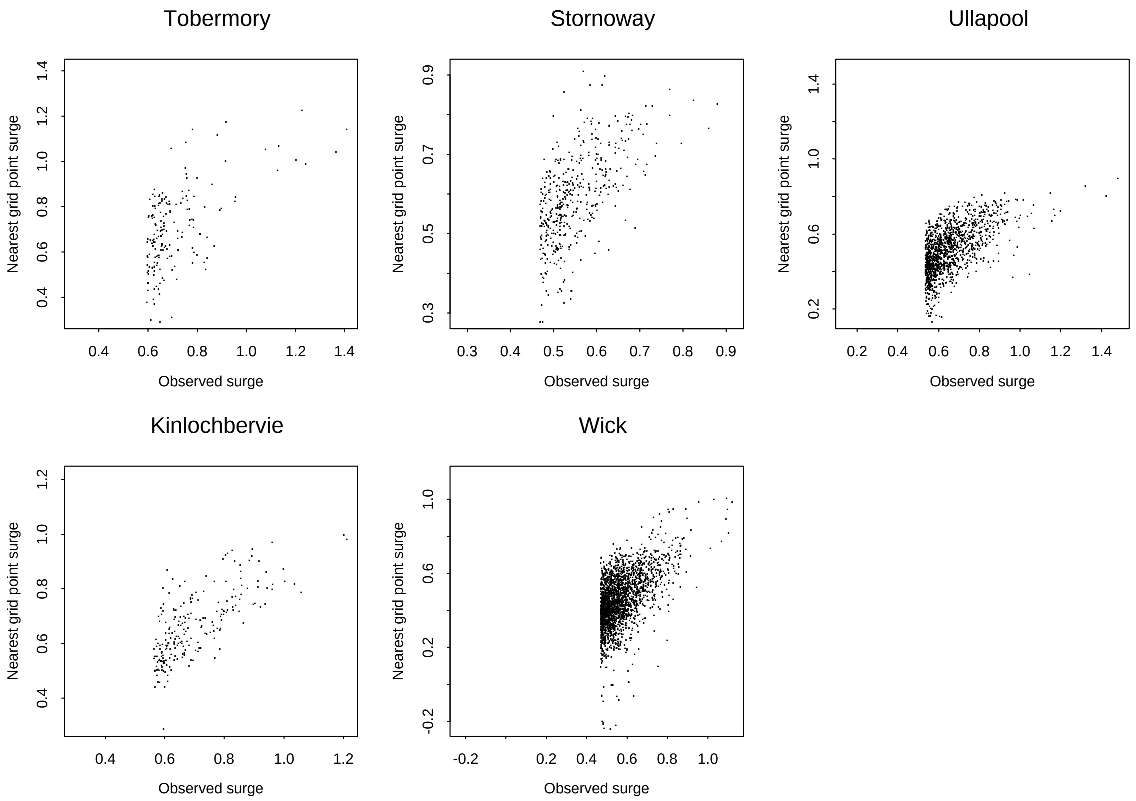

Figure 3.4: The nearest numerical model grid point data plotted against site data for Tobermory to Wick.

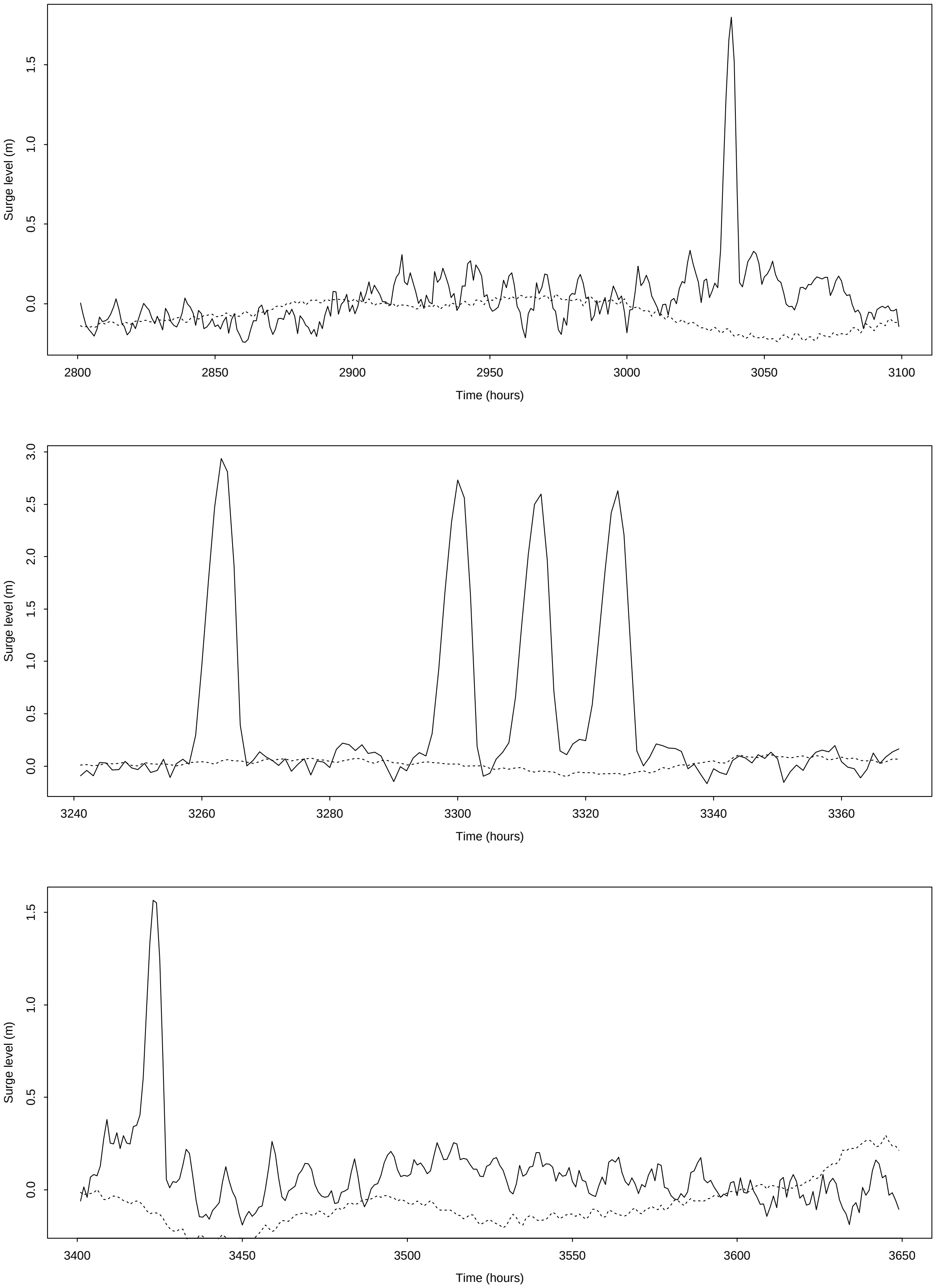

Figure 3.5: Periods of surge data from Immingham, and its nearest grid point are shown, for 1984. Time corresponds to the hour number in 1984. The solid and broken lines are observational data and numerical model data respectively.

3.1 Impact of Correcting the Immingham data

Having identified, and removed, the erroneous large surges from the Immingham data we now repeat the analysis in DT2. Here we show the resulting changes that the modification makes to the east coast spatial estimation. As information from each site is shared with other sites along the coast, an error at one site influences the estimates at neighbouring sites.

In the case of Immingham, estimates from Whitby to Lowestoft are influenced by this error, with the impact being less the further the site is away from Immingham. Estimates for more distant sites are not influenced by the error.

Figures 3.6-3.8 show the east coast spatial estimate (old and modified) for the GEV parameters μ, σ, and k respectively. Also shown on these plots are the site-by-site estimates. Here we see that the change to each parameter corresponds to a shortening of the tail of extreme surge levels.

Combining these parameter estimates, with the estimated interaction functions, which were not affected by the erroneous data, and the spatially mapped tide gives return level estimates for the entire coastline. This estimate, for different return periods, is shown in Figures 3.9-3.11. Site estimates are also shown on this figure. In addition, updated east coast spatial return level tables are provided in the Appendix (Tables 13.1–13.6). The impact of removing the erroneous surges at Immingham has been to reduce the return level estimates in the coastal region around the site. This modified spatial estimate is subsequently used as a reference, termed the UK east spatial estimate, when comparing the improvement in estimation given by inclusion of numerical model data.

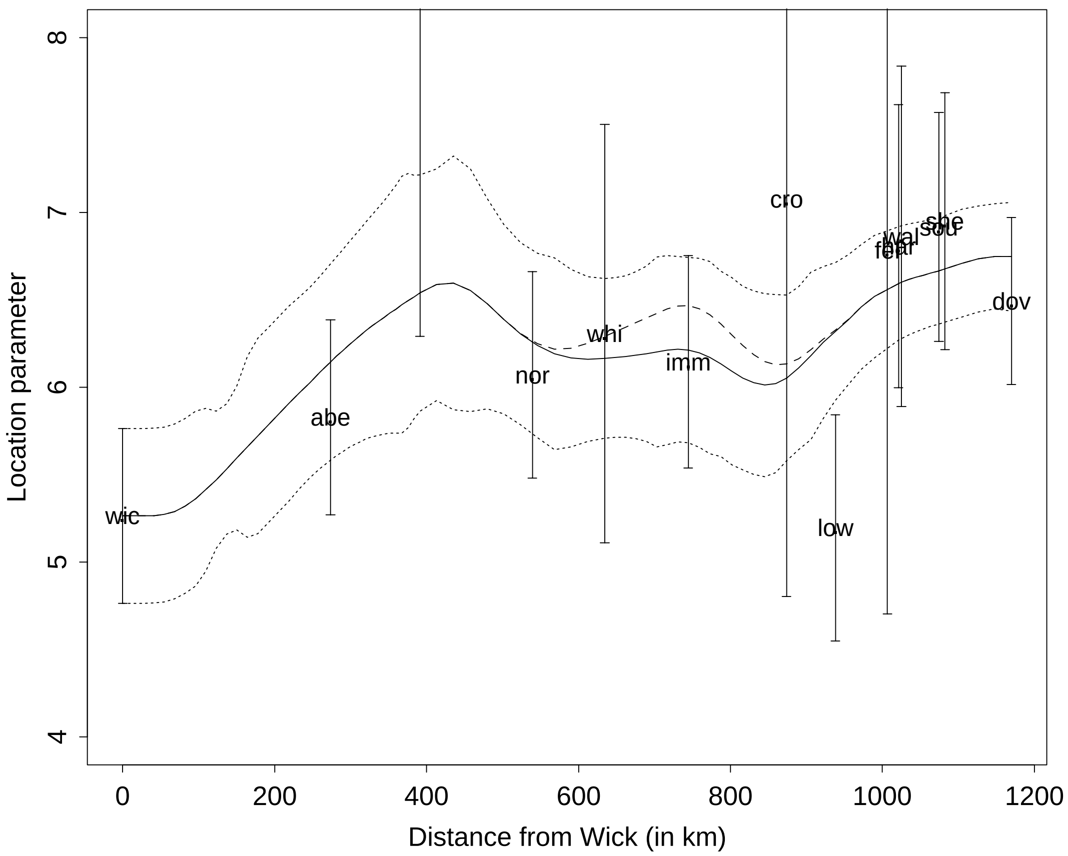

Figure 3.6: The point process location parameter for the surge, μ, against distance; the site-by-site estimates and the spatial estimate with approximate 95% confidence intervals. The solid line is the corrected estimate, and the broken line is the estimate given in DT2.

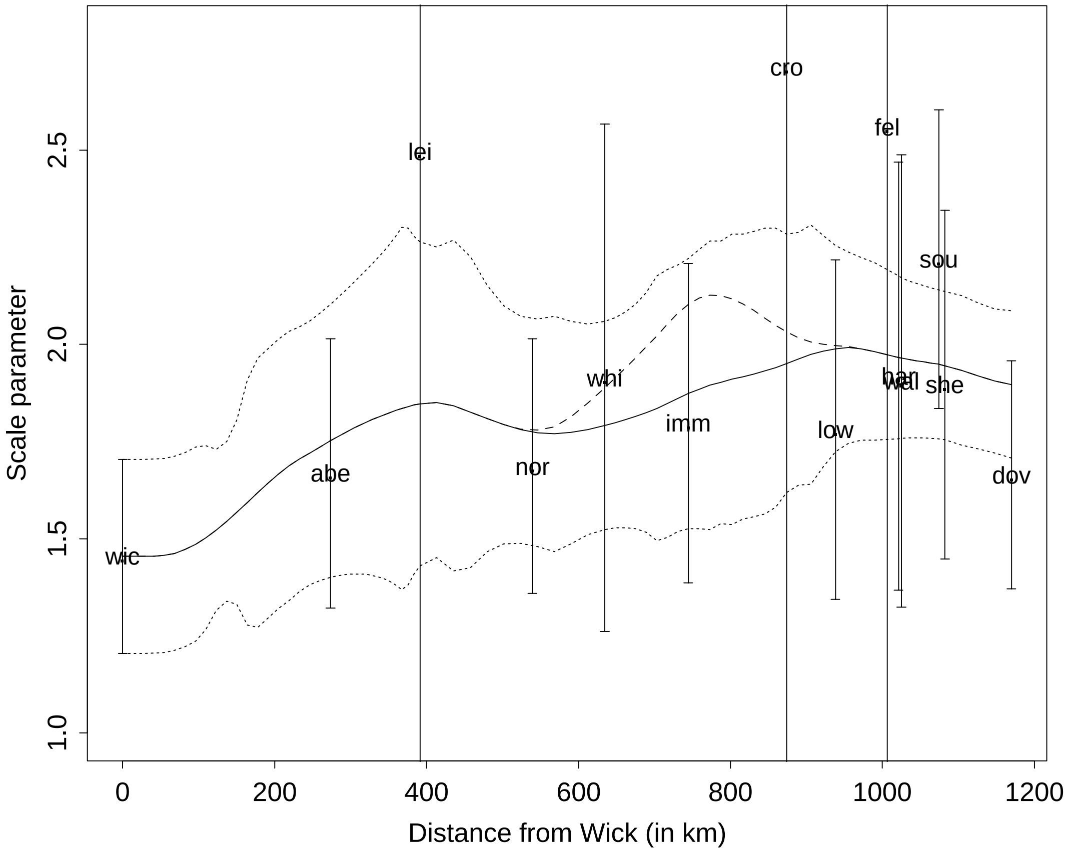

Figure 3.7: The point process scale parameter for the surge, σ against distance; the site-by-site estimates and the spatial estimate with approximate 95% confidence intervals. The solid line is the corrected estimate, and the broken line is the estimate given in DT2.

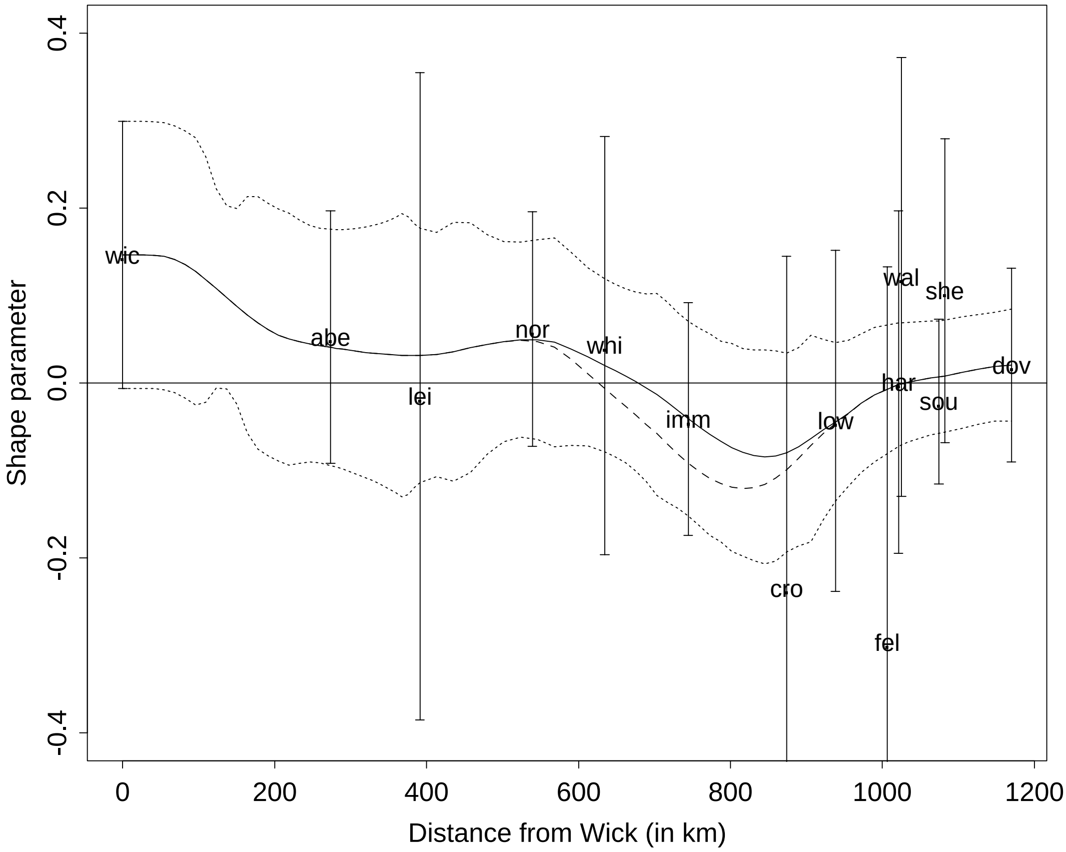

Figure 3.8: The point process shape parameter for the surge, k, against distance; the site-by-site estimates and the spatial estimate with approximate 95% confidence intervals. The line $k = 0$ is shown as a guide. The solid line is the corrected estimate, and the broken line is the estimate given in DT2.

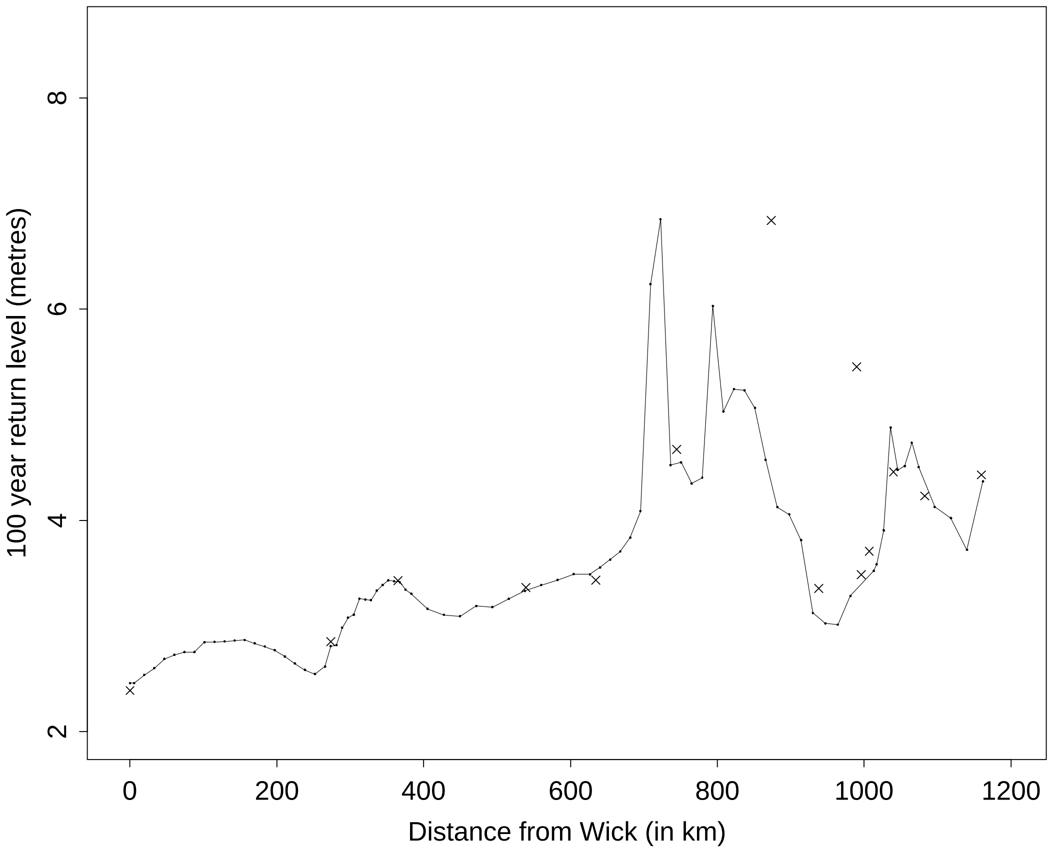

Figure 3.9: Spatial estimate of the 100 year return levels. The cross symbols represent estimates obtained from the SRJPM given in DT2. The estimates are to the datum of mean sea-level at each site.

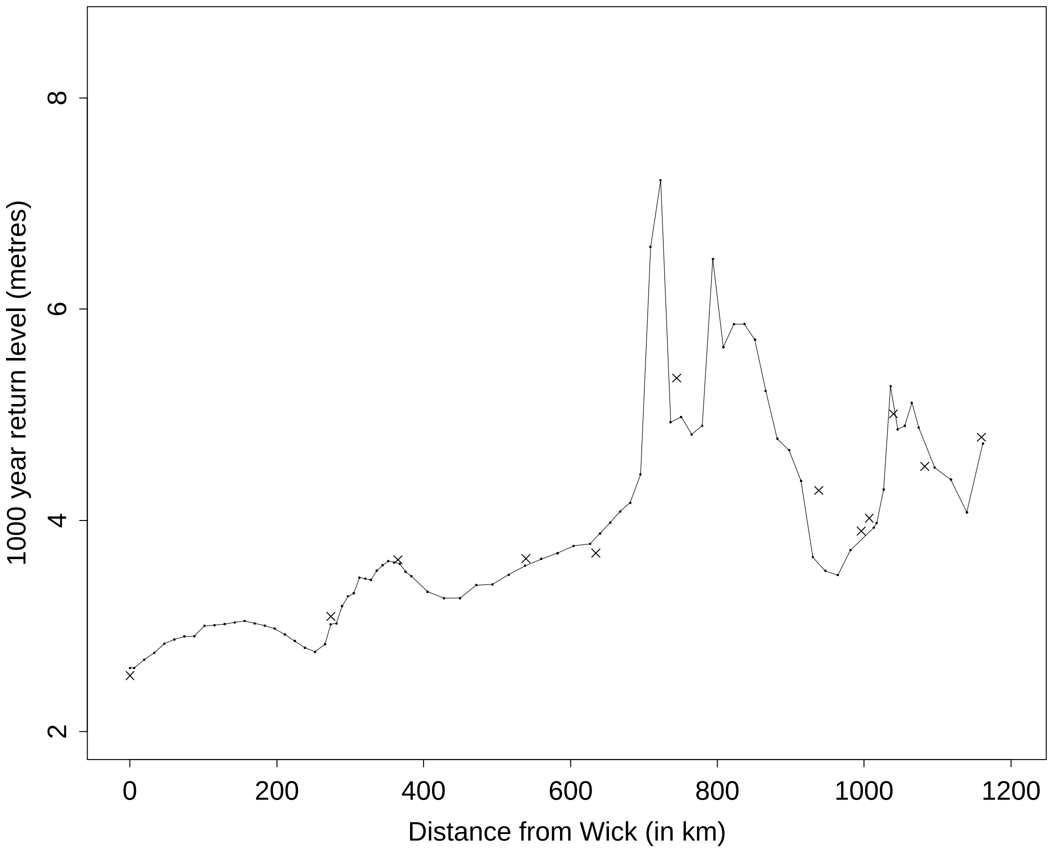

Figure 3.10: Spatial estimate of the 1000 year return levels. The cross symbols represent estimates obtained from the SRJPM given in DT2. The estimates are to the datum of mean sea-level at each site.

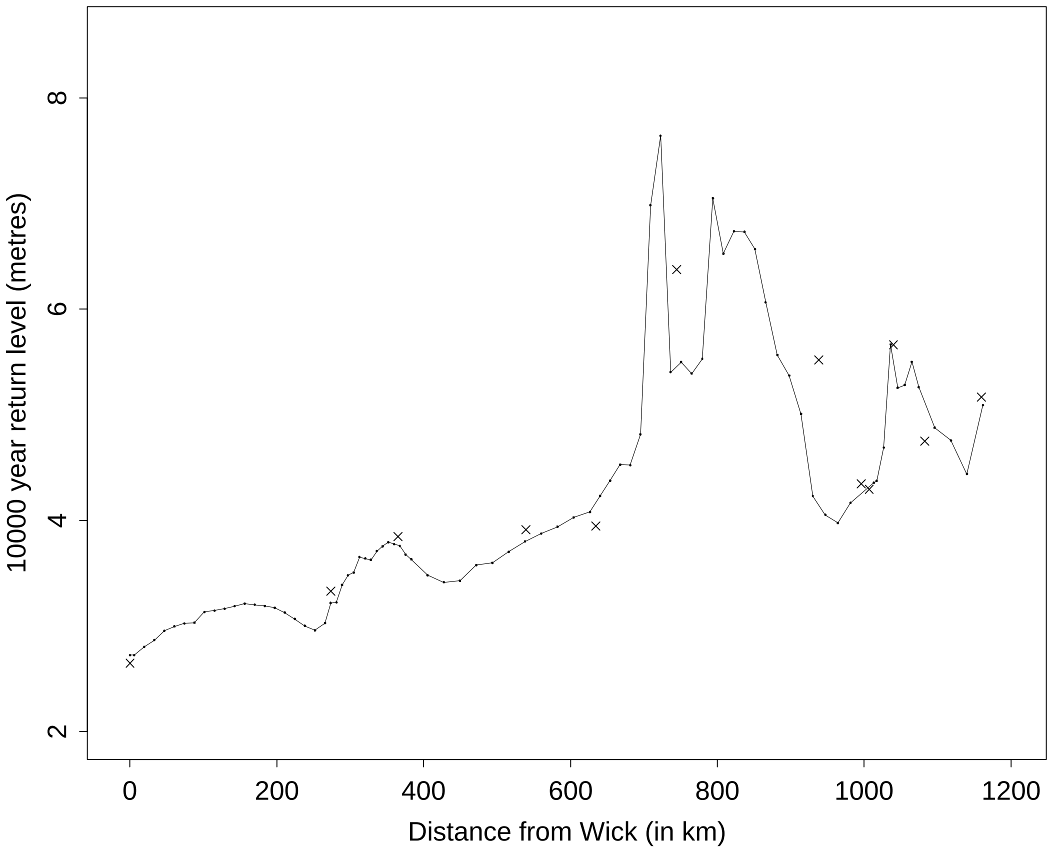

Figure 3.11: Spatial estimate of the 10000 year return levels. The cross symbols represent the estimates obtained from the SRJPM given in DT2. The estimates are to the datum of mean sea-level at each site.

Chapter 4

Tides

4.1 General description

A method was described in DT2 for estimating the the tidal series at any point on the East coast of the UK. In this report the method is extended to include the complete coast of mainland Britain but this involved certain adjustments because the south and west coasts proved to be more complex.

In general tides are only known accurately where a set of measurements exist: the objective for this study was to produce tidal series and characteristics for locations where there may never have been measurements. To achieve the required degree of accuracy, the problem was solved using the sites of the National Tide Gauge Network, and any suitable intermediate ports, as reference points around the coastline. Between these reference, or primary, points the tide is generated by a spatial interpolation scheme. The tide at the primary stations is of course known to a high degree of accuracy. At intermediate points an attempt is made to maintain this accuracy by employing output from a numerical model as a base function for the interpolation scheme. The European shelf 12km numerical tidal model (Flather and Smith, 1993) was used for this purpose.

Differences are calculated between the model and each primary point as a representation of the relationship between the two. These differences are then spatially interpolated using 'tilt' and 'bias' coefficients and used to adjust the model tide at each of the intermediate points. In practice the technique is applied to time series generated from harmonic constants which have previously been derived for the reference points and for each model grid point. Interpolation of the harmonic constants themselves proved to be insufficiently accurate.

The difference interpolation technique is discussed in detail DT2 and is not repeated here, however the adjustments that were made to the previous work to include the south and west coasts are discussed below.

4.2 Shoreline distance metric

As in the previous report, a reference coastline is adopted and adhered to. All primary stations, interpolated points, and many calculations are related to this coastline. It is in digitised form to make it useful for calculating along track distances etc. Obviously it has to be sufficiently accurate such that all stations actually lie on the digitised form of the coastline. However an over accurate representation leads to problems of tides in estuaries and in rivers. The method is not designed with these areas in mind as the model grid does not extend far enough. Where it is necessary to generate tides in shallow water/non-linear areas, alternative procedures will soon be available.

We have adopted a relatively high quality version of the coastline and named it the Shoreline Distance Metric (SDM). It is a subset of the World Vector Shoreline compiled by the U.S. Defence Mapping Agency and supplied to us by the British Oceanographic Data Centre. It has been reorganised only in the sense that each grid point follows the natural coastline in sequential order. The ordering begins at a point near Wick on the north coast of Scotland and progresses clockwise around the mainland.

Unlike the east coast, the south coast, but more particularly the west coast of Scotland has complex coastal geometry. This caused severe problems for the interpolation scheme. For example, at a resolution below the 12 km of the model grid it was impossible to distinguish a headland from a bay. The solution was to smooth the SDM to a resolution of approximately 20 km.

In a similar fashion to the SDM, those model grid points which lie adjacent to the coast follow a Model Distance Metric (MDM). This has a resolution of approximately 12km. Model grid points are identified with their nearest point on the SDM thus making it easier to extract the appropriate model harmonic constituents for the interpolation scheme.

The distance, latitude, and longitude of the coastal point nearest to each numerical model grid point obtained from the distance metric are shown in Table 4.1. Also the distances, latitudes and longitudes of the data sites are given in Tables 4.2 and 4.3.

4.3 Primary stations

The primary stations include all of the National Tide Gauge stations and several other ports for which a good quality sea level record is available. The suitability of a site as a reference station was judged on the quality of its data. Generally at least a year of good quality tidal measurements had to be available before a site was considered suitable. All the above stations have been analysed at one time or another for their harmonic constants. These constants act as the source of tidal predictions. At each station the number of constants differs according to the complexity of the tidal regime. In the very non-linear areas additional shallow water

No.	Lat.	Long.	Dist.(km)	No.	Lat.	Long.	Dist.(km)	No.	Lat.	Long.	Dist.(km)
89	58.64	-3.02	-5	30	52.18	1.62	1276	59	52.61	-4.13	2925
1	58.48	-3.05	5	31	51.83	1.25	1319	60	52.91	-4.26	2957
2	58.30	-3.25	35	32	51.46	0.72	1387	61	52.92	-4.62	3036
3	57.85	-3.78	105	33	51.38	1.24	1472	62	53.23	-4.15	3090
4	57.72	-3.28	215	34	51.10	1.26	1507	63	53.33	-3.77	3103
5	57.70	-2.79	247	35	50.90	0.71	1568	64	53.39	-3.21	3144
6	57.70	-2.29	281	36	50.73	0.24	1621	65	53.85	-3.06	3211
7	57.62	-1.83	309	37	50.82	-0.25	1653	66	54.17	-3.25	3305
8	57.50	-1.76	312	38	50.72	-0.79	1696	67	54.51	-3.64	3358
9	57.39	-1.86	359	39	50.78	-1.34	1756	68	54.86	-3.76	3448
10	56.85	-2.26	392	40	50.71	-1.75	1826	69	54.84	-4.26	3487
11	56.49	-2.72	443	41	50.61	-2.25	1843	70	54.63	-4.85	3593
12	56.20	-2.76	489	42	50.68	-2.69	1890	71	54.91	-5.18	3613
13	55.93	-2.23	606	43	50.63	-3.31	1941	72	55.00	-5.17	3674
14	55.70	-1.87	639	44	50.20	-3.73	2005	73	55.54	-4.69	3722
15	55.58	-1.64	687	45	50.31	-4.23	2066	74	55.58	-5.46	3944
16	55.43	-1.58	692	46	50.22	-4.80	2124	75	55.89	-5.69	4070
17	55.04	-1.43	720	47	49.96	-5.21	2181	76	56.13	-5.62	4155
18	54.81	-1.31	746	48	50.13	-5.71	2223	77	56.69	-6.19	4314
19	54.56	-0.79	812	49	50.03	-5.68	2228	78	56.75	-6.19	4354
20	54.35	-0.43	832	50	50.40	-5.15	2282	79	56.73	-6.23	4403
21	54.17	-0.25	850	51	50.74	-4.66	2334	80	57.48	-5.87	4545
22	53.67	0.11	917	52	51.15	-4.24	2393	81	57.87	-5.74	4546
23	53.45	0.19	995	53	51.46	-3.18	2557	82	57.83	-5.82	4563
24	53.09	0.29	1034	54	51.50	-3.75	2599	83	57.92	-5.62	4641
25	52.98	0.73	1136	55	51.54	-4.24	2648	84	58.43	-5.12	4690
26	52.95	1.23	1177	56	51.63	-4.78	2741	85	58.61	-4.77	4732
27	52.74	1.68	1205	57	51.87	-5.25	2798	86	58.55	-4.21	4762
28	52.81	1.57	1213	58	52.12	-4.73	2849	87	58.62	-3.67	4778
29	52.50	1.76	1231	59	52.61	-4.13	2925	88	58.66	-3.25	4793

Table 4.1: Reference table for locating a site on the distance metric, given its latitude and longitude.

Site	Abb.	Dist.(km)	lat.	long.	ACD Factor (m)
Wick	wic	1	58.44	-3.08	2.01
Aberdeen	abe	356	57.14	-2.08	2.52
Leith	lei	533	55.98	-3.17	3.19
North Shields	nor	724	55.01	-1.44	2.82
Whitby	whi	807	54.49	-0.62	3.28
Immingham	imm	940	53.63	-0.18	4.18
Cromer	cro	1212	52.67	1.73	2.79
Lowestoft	low	1235	52.47	1.75	1.57
Felixstowe	fel	1301	51.95	1.35	2.04
Harwich	har	1305	51.95	1.28	2.10
Walton on the Naze	wal	1318	51.85	1.27	2.20
Southend	sou	1388	51.53	0.72	2.89
Sheerness	she	1413	51.45	0.75	2.98
Dover	dov	1505	51.12	1.32	3.64
Newhaven	ne3	1610	50.78	0.07	3.63
Portsmouth	po2	1723	50.79	-1.12	2.82
Weymouth	wey	1846	50.60	-2.45	1.10
Devonport	dev	2059	50.37	-4.19	3.38
Newlyn	new	2198	50.10	-5.55	2.87
Ilfracombe	ilf	2402	51.21	-4.12	4.95

Table 4.2: Metric distances of the data sites, and their latitudes and longitudes. ACD is the adjustment that should be applied to our results in later sections, to adjust them from the MSL datum to ACD. The adjustments should be added to MSL to get ACD.

Site	Abb.	Dist.(km)	lat.	long.	ACD Factor (m)
Hinkley	hin	2471	51.21	-3.14	6.18
Avonmouth	avo	2517	51.50	-2.72	6.95
Newport	ne2	2534	51.55	-2.99	6.09
Swansea	swa	2616	51.62	-3.92	5.22
Mumbles	mum	2627	51.57	-3.97	5.18
Milford Haven	mil	2762	51.69	-5.02	3.76
Fishguard	fis	2825	52.00	-4.97	2.64
Barmouth	ba2	2937	52.72	-4.05	2.63
Holyhead	hol	3066	53.32	-4.62	3.14
Liverpool	liv	3148	53.41	-3.00	5.20
Heysham	hey	3243	54.03	-2.92	5.14
Port Erin	po3	3584	54.08	-4.77	2.92
Workington	wor	3368	54.65	-3.57	4.47
Portpatrick	por	3603	54.84	-5.12	2.10
Millport	mi2	3741	55.72	-4.91	1.99
Islay	isl	4035	55.63	-6.18	0.41
Tobermory	tob	4298	56.62	-6.07	2.71
Stornoway	sto	4597	58.20	-6.38	2.92
Ullapool	ull	4596	57.90	-5.17	3.09
Kinlochbervie	ki3	4677	58.45	-5.05	2.85

Table 4.3: Metric distances of the data sites, and their latitudes and longitudes. ACD is the adjustment that should be applied to our results in later sections, to adjust them from the MSL datum to ACD. The adjustments should be added to MSL to get ACD.

constituents are included to represent the severe distortion of the tide. At a minimum the number of constituents used for any primary station is 60 but is more usually 100.

The stations have been chosen to give a reasonable spatial coverage. Stations which are either too close together or are in the inner reaches of an estuary relative to the hydrodynamic model have been eliminated.

4.4 Hydrodynamic model grid

The harmonic constituents were extracted from the shelf surge-tide operational model - CS3 - which has a resolution of $1/60^\circ$ in longitude by $1/90^\circ$ in latitude, corresponding to 12km (Flather and Smith, 1993). The model is driven by fifteen constituents on the boundary and analysed for 50 model generated constituents at each grid point. For the present purpose only the model grid points adjacent to the coast are of interest and have been extracted.

Using 50 model constituents is not at odds with the number of constituents from the primary stations as they give a reasonable representation of the tide. Any departures from this simplified tidal representation is absorbed by the adjustment process, of bias and tilting, in the interpolation scheme.

4.5 The difference interpolation scheme

Software has been produced by the Proudman Oceanographic Laboratory to perform the interpolation scheme automatically.

4.6 Tests

Some tests were performed to assess the accuracy of the method. For the east coast this was easily achieved by computing harmonic constants for intermediate points using the interpolation scheme and comparing the results with expected values. For the south and west coasts this was done for a few points but there are substantially fewer tidal stations with which to compare interpolated results. Consequently, although the few stations tested gave satisfactory results, we concentrated on using the quantiles of the interpolated tidal probability distributions to assess accuracy.

4.7 Spatial mapping of tides

Figure 4.1 shows the $95\%, 99\%$ and 99.9% tidal quantiles for each data site (shown as a + symbol) and the continuous spatial tidal quantile curves for the whole coastline. Note that in Figure 4.1 the quantiles are based on a zero mean sea-level at each site, and are independent of the datum used to obtain the measured data.

In general, the tidal quantiles predicted by the numerical model are close to the quantiles at the sites. There are some discrepancies from using the spatial model around Harwich, Avonmouth, and Liverpool/Morecambe bays. However, by using the raw numerical model data, we can compare the estimates obtained from the spatial tide model, with estimates obtained directly from the numerical model data. Figure 4.2 shows the difference between the site estimates and both the spatial model and the raw numerical model respectively at each data site. It can be seen that the differences are smaller for the spatial model for nearly all data sites. Thus the spatial model improves on estimates obtained using the raw numerical model data alone. There are still problems with interpolation around the Severn Estuary and other complex coastal regions: updating these areas is discussed in Chapter 9.

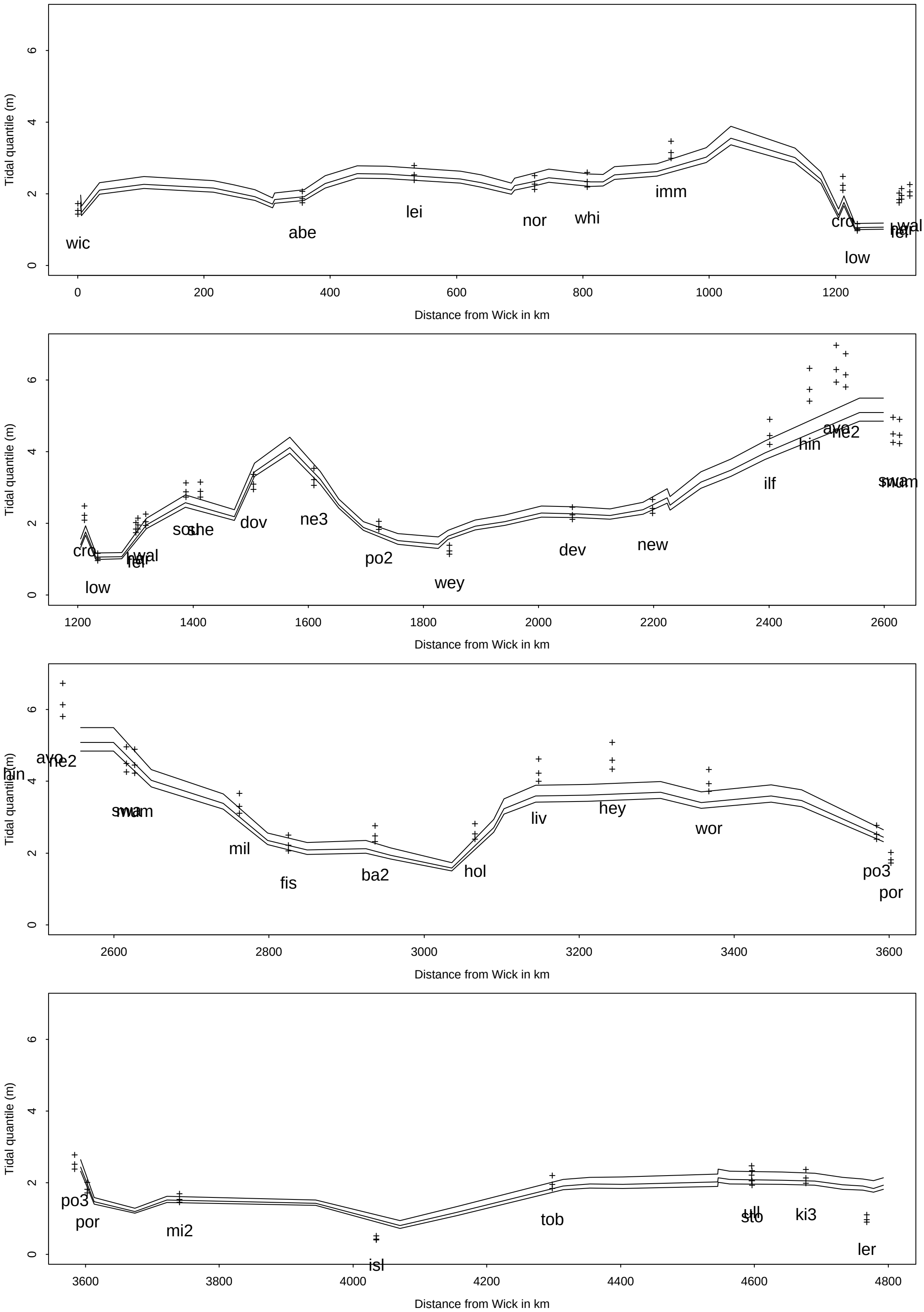

Figure 4.1: Quantiles of the tidal distribution at the sites, and at all distances obtained using the tide interpolation model. The quantiles shown are the 95%, 99% and the 99.9% levels. The + symbols indicate the corresponding quantiles, based on tidal predictions from actual observations, for the data sites.

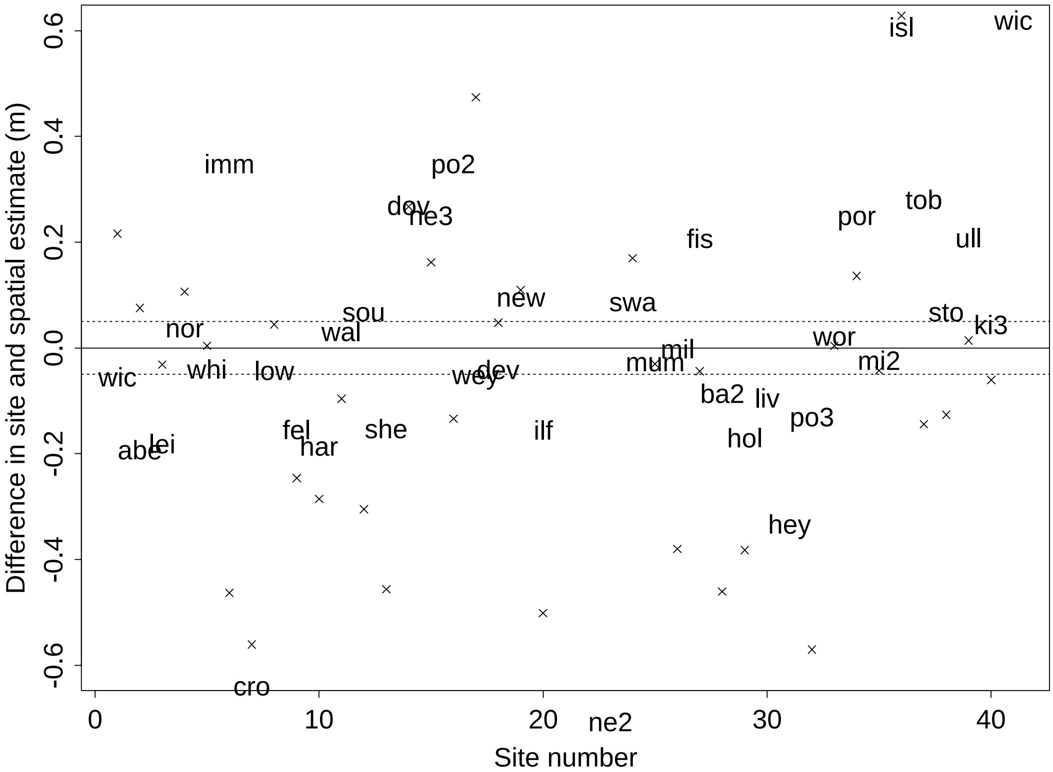

Figure 4.2: Comparison of estimates of the 99% tidal quantile at the sites. The crosses represent the difference in the estimated quantile from the site and the unadjusted (nearest) numerical model data, and the site names are the difference between the (nearest grid point) spatial tide estimate and the site tides. The broken lines, given as a guide, are differences of plus and minus 5cm.

Chapter 5

Trends

The two processes which influence the spatial behaviour of observed extreme sea-level trends are

- eustatic trends (actual sea-level trends)
- isostatic trends (vertical land level trends).

The important parameter, for purposes of estimating return levels, is the observable trend at the coastal position, i.e. the composition of the isostatic and eustatic trends. In this chapter we obtain a spatial estimate of the observed trend around the UK coastline. We extend the methods of DT2, who obtained a trend for the east coast, to the whole coastline. The basic idea is to spatially smooth the marginal trends so that there is a partial transfer of information to sites with short data series from those with more precise estimates. Before giving the spatial estimate, we discuss how we use the numerical model data to improve trend estimation at a site.

In Section 5.1 we examine trends in the numerical model data itself. These turn out to be of limited use for obtaining future return level estimates along the coastline. In Section 5.2 and 5.3 we look at how the numerical model can be used to improve trend estimation at a site. The idea is to exploit the correlation in the nearest grid point data to a site in order to reduce the variability in the data, and thus to improve trend estimation. There are two ways to do this. Firstly, we can use annual mean sea-level data from sites and the numerical model and exploit dependence in these. This approach is described in Section 5.2. The second approach is to exploit the dependence in the hourly data from a site and the nearest grid point, as observed in Chapter 2. Regression models for this approach are discussed in Section 5.3. These models play an important role in later analyses in Chapter 6.

Finally in Section 5.4 we obtain a spatial trend estimate for the UK coastline. Throughout this chapter we follow DT1 and DT2 and assume that trends in extreme and mean sea-levels are the same. Examination of extreme trends using the numerical model data presents an interesting problem for future work.

5.1 Trends in the numerical model

Trends in the numerical model data contain two components: a component of the eustatic sea-level trend and other components due to bias or other effects in the numerical model. Note that the numerical model does not contain the actual eustatic (global) water level rise, but only one component of this trend-that due to changes in meteorological events. Figure 5.1 shows the

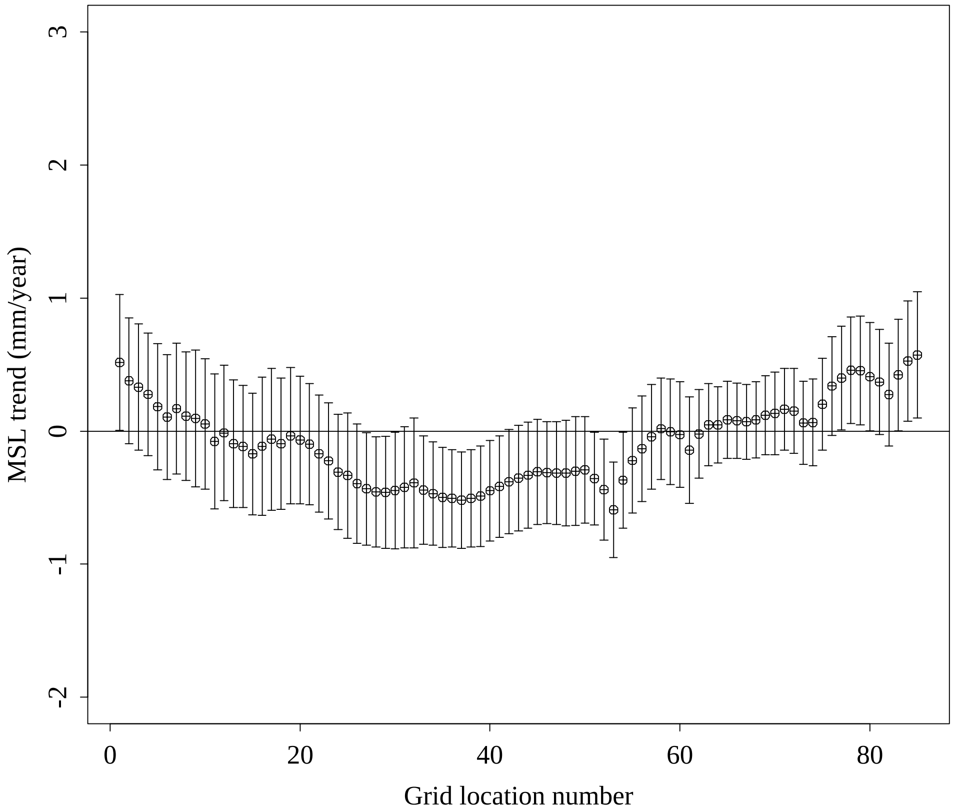

Figure 5.1: MSL trend estimates and 95% confidence intervals for the coastal numerical model data.

trend estimate obtained using annual mean sea-level data from each grid point. The trends are small and in general not significant and so could be ignored. Our approach is to remove the trends at this stage in order to avoid potential bias in our subsequent estimates.

5.2 Trend estimation: mean data

Consider a particular data site and its nearest grid point; let $\{m_i^* : i \in I_n\}$ be the numerical model mean sea-level (MSL) in year i and let $\{m_i : i \in I_s\}$ be the annual MSL in year i at the site, obtained from the tide-gauge data. Here I_n and I_s are the set of years that contain numerical model and site data respectively. The usual estimate of the trend is given by standard linear regression (for example Woodworth, 1987) i.e. by fitting

$$m_i = \alpha + \beta(i - i_0) + \epsilon_i$$

where the ϵ_i are normally distributed white noise random variables, i.e. $\epsilon_i \sim N(0, \sigma_1^2)$, i_0 is a base year, and α and β are the intercept and trend parameters respectively. Denote the estimated trend from fitting this model by $\hat{\beta}_{site}$. The numerical model data does not contain a trend (since any trend was removed earlier), so we can write

$$m_i^* = \alpha^* + \epsilon_i^*,$$

for $\epsilon_i^* \sim N(0, \sigma_2^2)$. Now consider the series $\{m_i - m_i^* : i \in I_n \cap I_s\}$. This will have the same trend as m_i and so we can write

$$m_i - m_i^* = \alpha - \alpha^* + \beta(i - i_0) + \epsilon_i^+.$$

where $\epsilon_i^+ = \epsilon_i - \epsilon_i^*$. A bivariate version of the Central Limit Theorem suggests that ϵ_i, and ϵ_i^* are bivariate normally distributed with

$$[\epsilon_i, \epsilon_i^*] \sim N_2(0, 0, \sigma_1^2, \sigma_2^2, \rho)$$

where ρ is the correlation between the site and the numerical model MSL series. Thus the variance of ϵ_i^+ is given by

$$\text{var } [\epsilon_i^+] = \text{var } [\epsilon_i - \epsilon_i^*] = \sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2$$

which will generally be less than the variance of ϵ_i for positive correlation between the two sites. For example if $\sigma_1 = \sigma_2 = \sigma$ then var $(\epsilon_i^+) = 2\sigma^2(1 - \rho) < \sigma^2$ if $\rho > 0.5$.

Table 5.1 shows the trend estimates obtained using the two methods, i.e. (i) site MSL data, and (ii) site MSL minus grid point MSL, and shows how the standard errors of the estimates are generally reduced by using the grid point data. Thus by using the numerical model data to obtain a series of differences we obtain improved trend estimates at many sites.

5.3 Trend estimation: hourly data

Now consider how the hourly numerical model data can be used to improve trend estimation. For a particular site, one way of estimating the trend is to fit a linear model (with trend) and treat the numerical model hourly data as a covariate. More explicitly, let Y_t be the hourly site data at time t, and let $V_{t,k}$ be the corresponding hourly data at time t for the kth nearest grid point to the site. Then we fit a linear model with 9 covariates, of the form:

$$Y_t = \beta_0 + \sum_{k=1}^{5} \beta_k V_{t,k} + \beta_6 V_{t+1,1} + \beta_7 V_{t-1,1} + \beta_8(i_t - i_0) + \epsilon_t. \tag{5.3.1}$$

	Site data		Difference		Ratio
Site	Est	se	Est	se	
Wick	2.15	0.807	1.58	0.586	0.727
Aberdeen	1.91	0.581	1.33	0.518	0.892
Leith	8.50	15.922	-15.10	3.705	0.233
North Shields	2.87	1.186	2.58	1.161	0.979
Whitby	1.05	1.965	0.53	1.377	0.701
Immingham	1.56	0.748	1.93	0.727	0.971
Cromer	-4.76	8.395	-6.72	7.543	0.899
Lowestoft	4.48	1.031	4.70	1.076	1.044
Felixstowe	-9.77	7.216	-11.05	5.688	0.788
Harwich	1.17	1.154	1.04	1.22	1.057
Walton on the Naze	3.13	2.089	4.39	1.417	0.678
Southend	1.28	2.874	1.26	2.565	0.893
Sheerness	3.95	0.931	5.00	0.937	1.006
Dover	3.37	0.47	3.84	0.408	0.869
Newhaven	0.48	0.808	0.92	0.50	0.619
Portsmouth	-3.75	5.875	-6.97	6.421	1.093
Weymouth	-0.54	10.501	13.72	0.241	0.023
Devonport	-0.91	7.212	6.47	0.653	0.091
Newlyn	0.48	0.808	0.92	0.50	0.619
Ilfracombe	4.48	1.293	5.09	1.224	0.947
Hinkley	15.73	24.759	32.00	4.463	0.180
Avonmouth	-0.46	0.861	-0.44	0.36	0.418
Swansea	1.40	0.692	2.07	0.524	0.757
Mumbles	-7.06	7.21	-1.54	5.555	0.770
Milford Haven	-1.17	1.209	-0.78	1.071	0.886
Fishguard	1.81	0.982	2.51	1.037	1.056
Holyhead	3.48	0.605	3.35	0.605	1.000
Liverpool	-1.37	4.11	3.41	1.77	0.431
Heysham	3.97	1.056	3.56	1.067	1.010
Portpatrick	6.89	1.001	6.36	0.766	0.765
Millport	-5.41	4.095	-7.55	2.129	0.520
Islay	-1.28	4.225	8.98	0.875	0.207
Stornoway	-20.48	6.836	-19.76	3.349	0.490
Ullapool	3.77	1.032	2.85	0.695	0.673
Kinlochbervie	0.59	3.551	0.84	0.916	0.258

Table 5.1: Mean sea-level trend estimates: at the sites, and for the difference between site MSL and numerical model MSL. Ratio gives the ratio of the standard errors for the two methods-with values less than one indicating the numerical model data helps.

Here the β_8 and β_0 parameters are the trend and intercept, and $\beta_1 - \beta_7$ are parameters which correspond to contributions from spatial and temporal covariates ($\beta_1 - \beta_5$: the nearest five grid points, β_6: the nearest grid point lagged by -1 β_7: the nearest grid point lagged by 1.) Standard selection techniques can be used to parsimonise this model; this is discussed in Section 6.2. For purposes of trend estimation, at this stage we assume that the 5 nearest points provide all the information; other points do not provide any extra independent information. Using model (5.3.1), much of the variation is explained by the $V_{t,k}$ terms, and this gives an improved estimate of the trend. The data are serially correlated which means that standard errors are underestimated if calculated in the usual way. Approximate standard errors are given by re-fitting (5.3.1) using every 40th hourly observation which are assumed to be independent observations.

5.4 Spatial estimation

The two methods discussed above lead to improved trend estimation at some sites. Section 5.2 illustrates how removal of effects can improve the estimation of trends based on mean sea-level data. Section 5.3 exploits dependence in the hourly data values. In practice there is little difference between the two, and we use the first method only. Thus we combine the first method with the methods described in DT2 for site-by-site trend estimation. For each site the trend estimate is obtained in the same way as DT2 for the east coast sites. For other sites, the method uses the estimates in Table 5.1 for sites with enough data to give reasonable estimates. This is all sites in Figure 2.1 except for Portsmouth, Weymouth, Devonport, Hinkley, Port Erin, Millport, Islay, Tobermory, and Stornoway.

The spatial estimate of the trend is then based on these best available estimates of the trend at each site. The site-by-site trend estimates, and respective 95% confidence intervals are shown on Figure 5.2. The length of record, the form of data, and the self consistency of the data at the site affect the uncertainty of the estimates which is much larger at some sites than others.

Also shown on Figure 5.2 is the fitted smooth spatial trend with associated 95% confidence interval. The spatial model weights the spatial fit to the site-by-site estimates in accord with the standard error at each site and the proximity and value of trend estimates from neighbouring sites. Enlarged versions of the spatial estimate are given in Figures 5.3 and 5.4. Figure 5.3 is for the east coast only, and compares the DT2 estimate with the new estimate, and Figure 5.4 shows the spatial estimate for the whole coastline.

For the east coast, the spatial estimate is basically the same as that in DT2. The trend estimate around Wick is improved as now the coastline is wrapped around Northern Scotland, and so information from sites such as Ullapool is transferred to Wick. For the other coasts, the same general pattern is observed, i.e. for isolated sites which have a precise site-by-site trend estimate, the spatial trend is approximately the same as the site-by-site estimate. When the

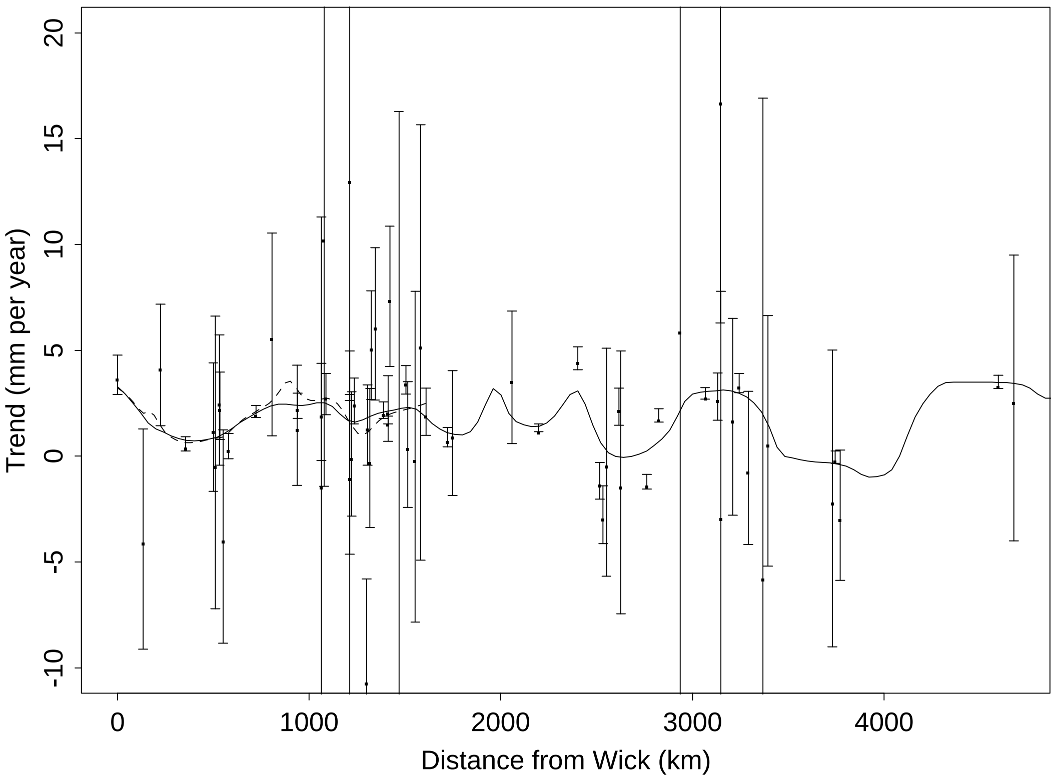

Figure 5.2: The spatial trend estimate for the UK coastline. All data have been used to obtain the trend estimate, including the numerical model data to reduce the variability in the annual mean sea-level data. Humber estuary sites are excluded, for reasons discussed in DT2. The marginal estimates are from sites which have more than 4 years of hourly, mean sea-level or annual maximum data.

site-by-site estimate for an isolated site is poor, then the spatial information plays more of a role in producing the spatial estimate. The south coast has some long historical records which lead to site estimates with very tight confidence intervals. Spatially these estimates are inconsistent and so result in a spatial estimate which varies rapidly over this coastal region.

In the remainder of the analysis the trend is fixed at the spatial estimate before estimating the other features of the model. This is the approach taken in DT2 and gives site-by-site estimates of the other parameters which exhibit greater spatial smoothness and thus simplifies the physical interpretation of the parameters.

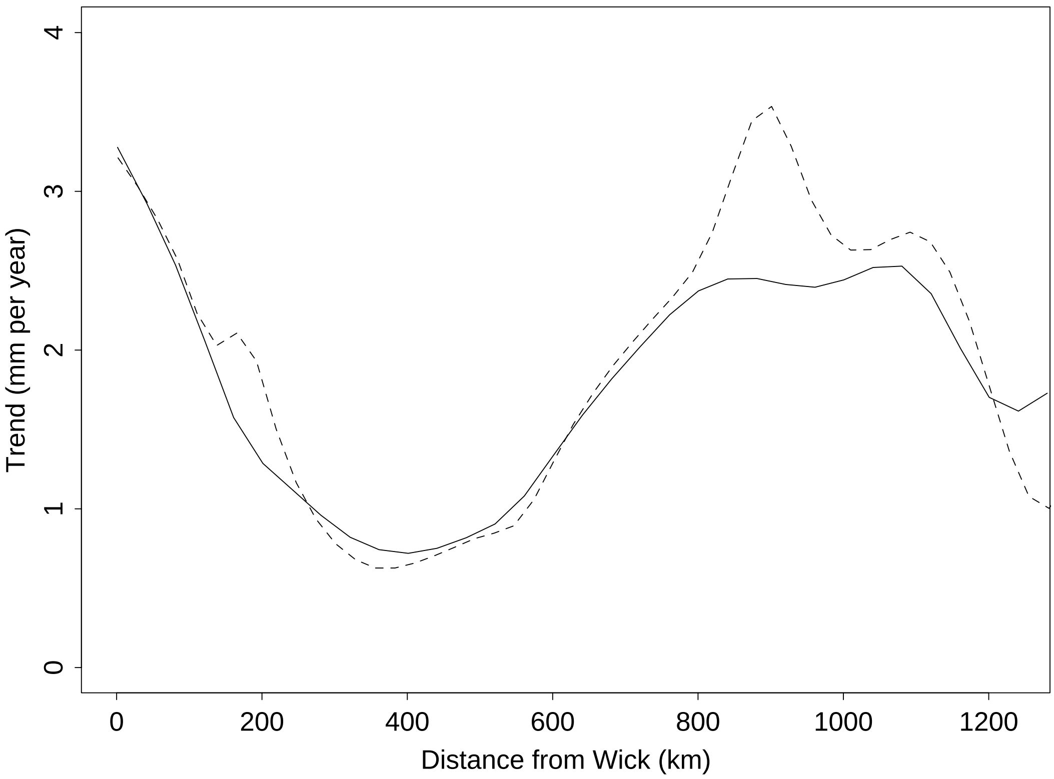

Figure 5.3: The spatial trend estimate for the east coast (solid line) and the estimate obtained in DT2 (broken line).

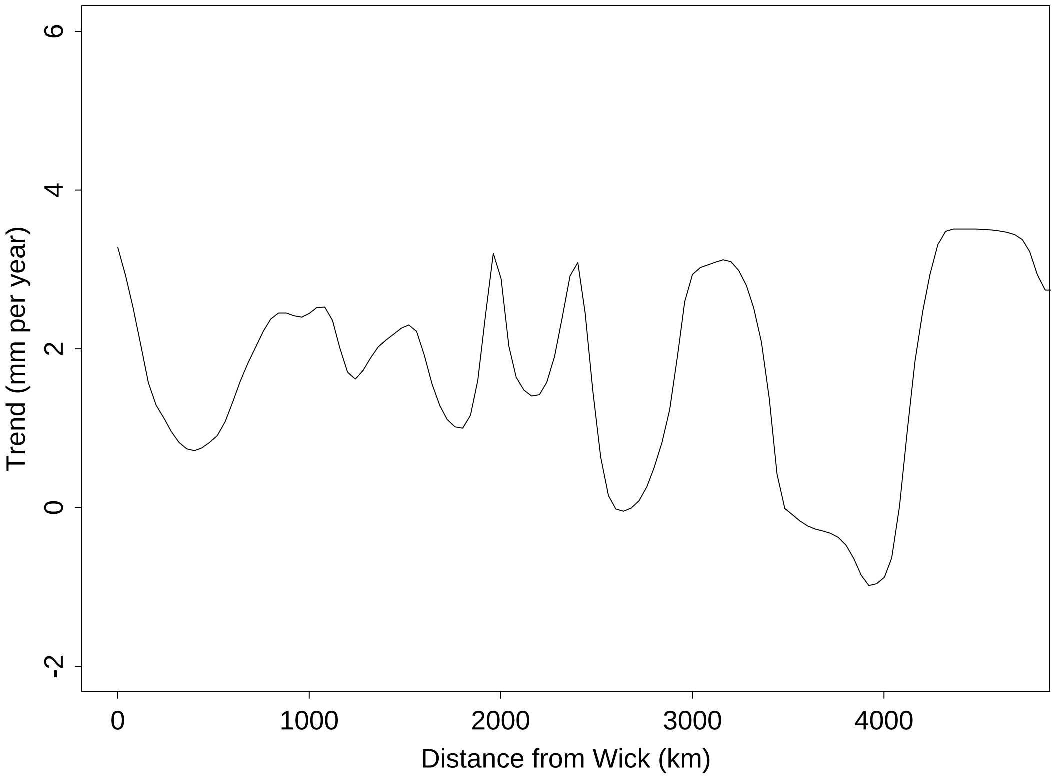

Figure 5.4: The spatial trend estimate for the UK coastline.

Chapter 6

Calibrating the numerical model data

The purpose of the remainder of the report is to use the numerical model data to give a spatial estimate of the return level around the entire UK coastline. The high resolution of the numerical model grid means that for most of the coastline complete spatial information can be obtained by estimating return levels at each grid point and obtaining estimates between grid points by linear interpolation. Thus we describe methods to obtain return level estimates at each grid point around the coast. The most direct approach, which is termed **Approach I**, is to apply the best site-by-site method, such as the SRJPM described by DT2, to the 39 years of hourly numerical model data at each grid point. This gives an estimate of return levels at each grid point that is based solely on the numerical model data. If the numerical model does not reproduce the true behaviour of the sea-level at a coastal point, then these estimates will be inaccurate and may be subject to bias. There are many possible reasons why the numerical model data may not reflect the actual sea-level behaviour at the nearby coastline. For example:

- there may be random or systematic errors in the numerical model itself, or in the input variables to the model
- The numerical model data is formed as an average over a square region of 36×36km. The averaged behaviour may differ from the behaviour at the unique point of the grid.
- on-shore sea-levels may behave differently to those just offshore near to the same location.
- surges may take time to travel from the grid point to the coastline. In this case measurements may be slightly lagged, causing the hourly observational data to differ.

Thus some form of adjustment is required in order to exploit correctly the numerical model data. Our approach is to calibrate the model data based on overlapping site data defined in

Chapter 2. The calibration factors are then evaluated for the overlapping data for every grid point that has a nearby data site. These factors are then calculated around the whole coastline by spatially smoothing them with respect to distance. The re-calibration is applied together with the full 39 years of numerical model data at every grid point. This provides the required estimates at every grid point. In the following chapters, we propose 3 methods that can be used as a basis for the calibration. Including no calibration, there are 4 approaches:

- **Approach I: Raw numerical model**
  Direct application of the spatial revised joint probabilities method (SRJPM) at each grid point.

- **Approach II: Calibrate data**
  Calibrate the numerical model time series data by comparison with data at the sites, and then apply the SRJPM to this calibrated data set to obtain return level estimates along the coastline.

- **Approach III: Calibrate return levels**
  Apply the SRJPM directly to the numerical model data as in **Approach I**, and obtain estimated spatial return level curves along the coast. These are then adjusted by comparing return level estimates with site return level estimates obtained from the SRJPM.

- **Approach IV: Calibrate SRJPM parameters**
  Apply the SRJPM to the numerical model data and separately adjust each component in a smooth way. These adjusted estimates are then recombined within the SRJPM to give return level estimates at each point. The method is similar in principle to the method applied in DT2, Chapter 12.

In Sections 6.1-6.3 respectively, the first three of these are described and applied to the UK data. In Chapter 7, we describe **Approach IV** and compare the results from the four approaches.

Strategy

In this section and throughout the report, the performance of any spatial method is assessed by comparison of the spatial estimates with both the site estimates, obtained using data from the site, and the east coast estimates of DT2 where available, at the site locations. Throughout these comparisons we will focus on estimates for the data sites. At the initial stage of development we make comparisons only at sites with records of 10 years or more of data. This reduces the number of sites considered to 16. As we initially wish to compare statistical properties of the spatial mapping we use the site tides rather than the spatial tides developed in Chapter 4. This means that any observed differences between spatial and site estimates are due purely to the handling of the surges. Also, to simplify comparisons, in most cases, we omit the estimates for the overlapping grid point data at the site.

6.1 Approach I: Raw numerical model

The simplest approach to using the numerical model data is to apply the SRJPM directly to the numerical model data. This is only a reasonable approach if the model data provides a realistic representation of the observational data. Application of this method, as described in DT2, leads to return levels around the coastline plotted in Figure 6.1 and 6.2. The previous estimates obtained using site data in the SRJPM and the spatial east coast estimate in DT2 are also shown on the plots.

The clearest graphical comparison of each method is given by plotting the port diagrams for each of the 16 sites with long data records. Figures 6.1 and 6.2 show that the agreement of the raw numerical model data estimates with the site estimates varies over the sites. For example

- at Aberdeen, Fishguard, Holyhead, and Portpatrick, the agreement is very good.
- at Wick, Harwich, Southend, Sheerness, and Dover, there is a fair agreement for low return periods, but the raw estimates are larger at long return periods.
- at North Shields, Immingham, Newlyn, Milford Haven, and Ullapool the raw numerical model estimates under-estimates for all return levels relative to the site estimates.
- at Lowestoft, **Approach I** gives an estimate which agrees well with the east coast spatial estimates of DT2 but not with the site data.

At this stage we cannot assess whether the differences are due to poor numerical model data or poor site data. **Approaches II-IV** allow us to make this distinction and suitably correct for any inadequacies in the numerical model data.

Conclusion

This approach has shown that the numerical model data is giving a valuable starting point to estimating extreme levels at data sites and therefore at other coastal locations as well. The following methods look to improve the estimates given here by taking three fundamentally different calibration routes: (i) calibrating data, (ii) calibrating final estimates, and (iii) calibrating intermediate estimates in **Approaches II** to **IV** respectively.

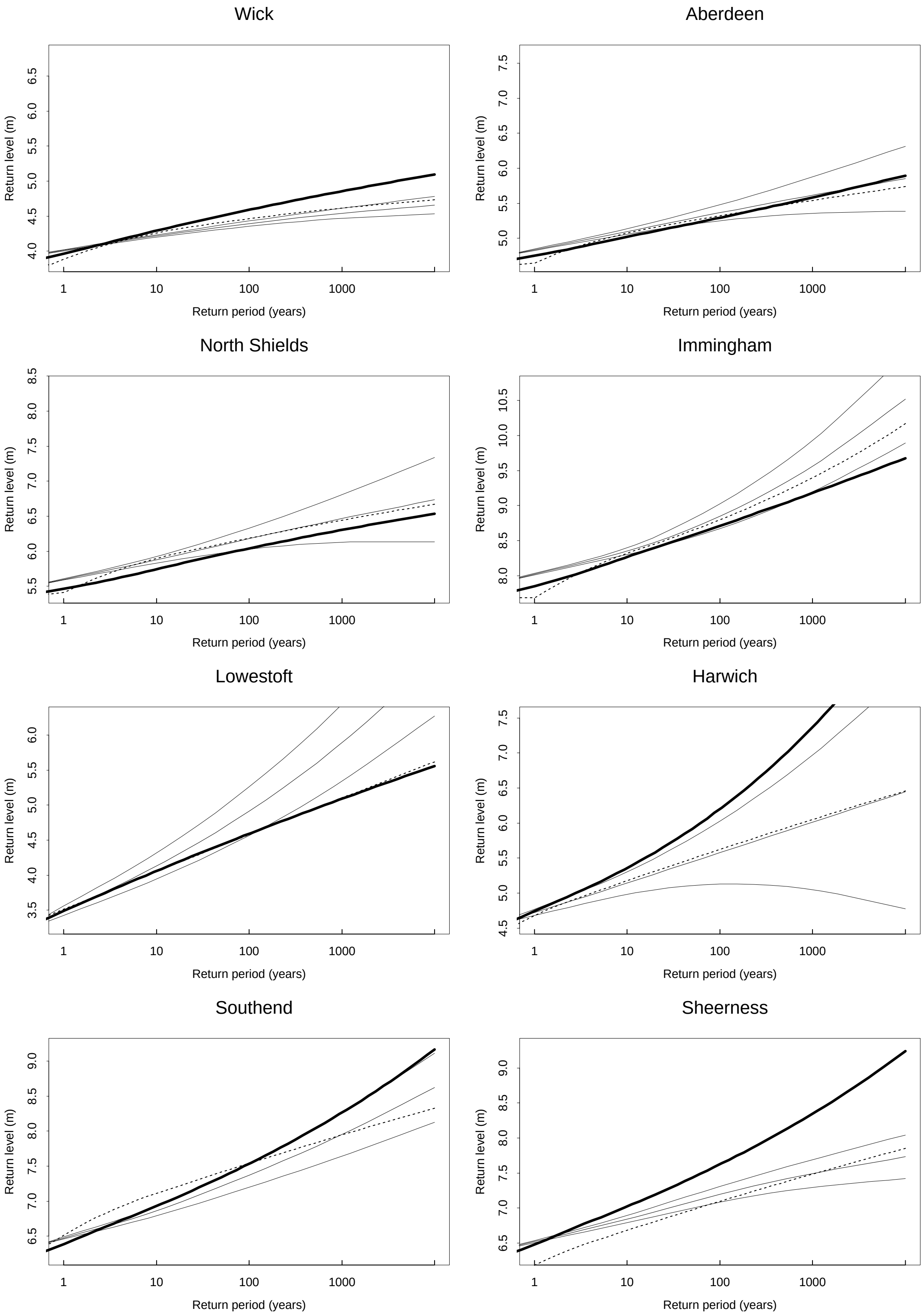

Figure 6.1: Port diagrams at the sites for **Approach I**. The bold lines are for **Approach I**. Site values, with 95% confidence intervals, are faint continuous lines, and the east coast estimate is shown as a broken line where available.

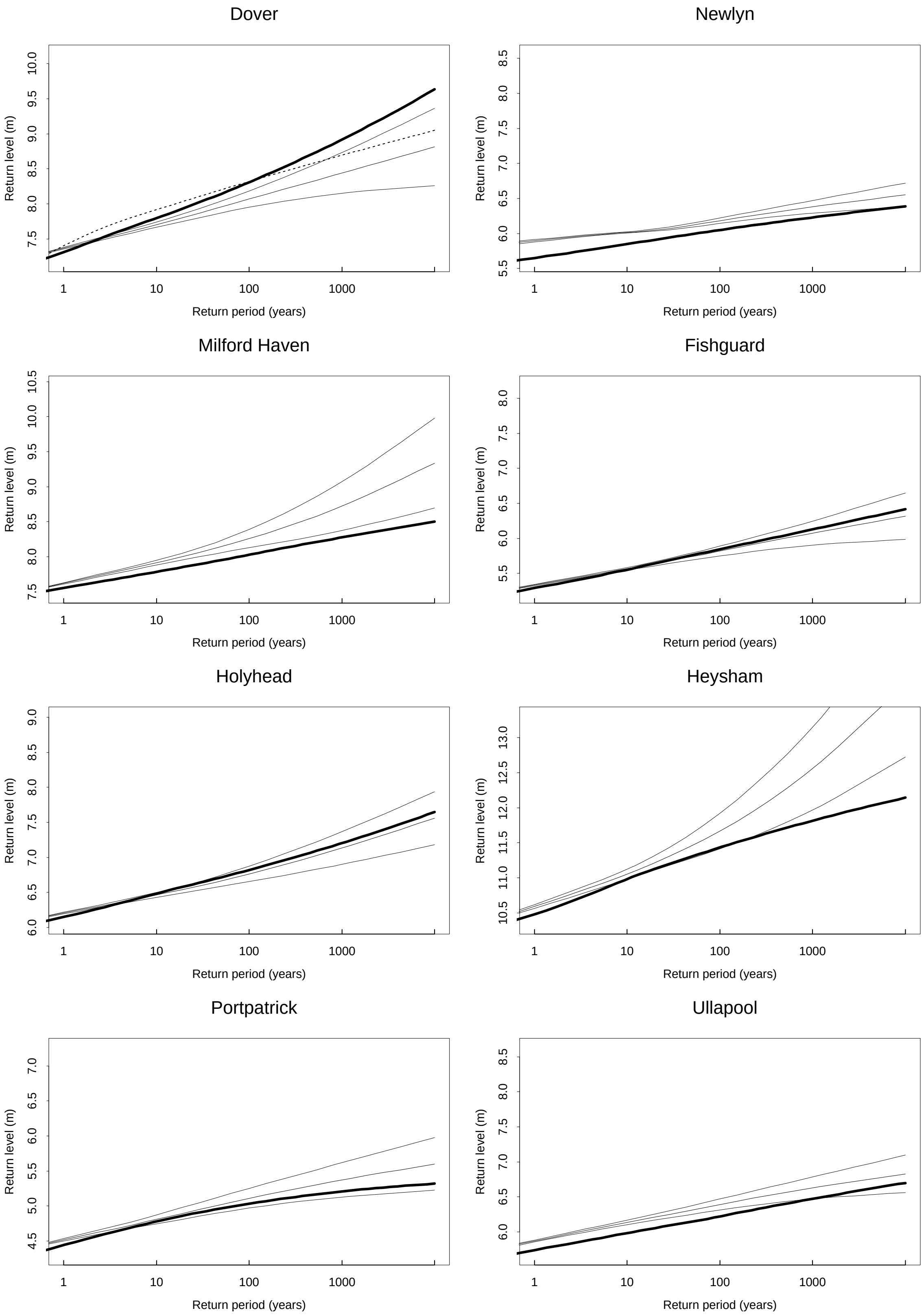

Figure 6.2: Port diagrams at the sites for **Approach I**. The bold lines are for **Approach I**. Site values, with 95% confidence intervals, are faint continuous lines, and the east coast estimate is shown as a broken line where available.

6.2 Approach II: Data calibration

6.2.1 Calibrating the overlapping data

We investigate how the numerical model hourly data can best be exploited to give data that is representative of the true behaviour at the coastline. Since Figure 2.4 (p32) shows that there is a strong relationship between the nearest numerical model data and the site, a natural first step is to examine a regression of the site data on the overlapping numerical model data to see if a simple linear adjustment to the numerical model data is sufficient. Following the notation of Chapter 5, we fit the model (5.3.1) but without the trend which has been removed in previous sections. Thus we fit

$$Y_t = \beta_0 + \sum_{k=1}^{5} \beta_k V_{t,k} + \beta_6 V_{t+1,1} + \beta_7 V_{t-1,1} + \epsilon_t. \tag{6.2.1}$$

for each of the 41 sites in Tables 4.2 and 4.3 . Table 6.1 gives a summary of various nested model fits obtained for Wick; the pattern is similar for other sites. The nearest grid point (corresponding to β_1) appears to contain most of the significant independent information. The time taken for the surge to travel between grid point and the site (β_6 and β_7) is not a significant effect, and so the adjacent time points are not required in the model. There are some sites where the second nearest grid point contains some additional information to the nearest point, however, mostly the nearest grid point contains nearly all independent information, and so we adopt the simple model

$$Y_t = \beta_0 + \beta_1 V_{t,1} + \epsilon_t. \tag{6.2.2}$$

for all sites and nearest grid points. This gives an approximate linear relationship of site data and overlapping data. The solid lines in Figures 6.3-6.4 show these fitted regressions at each of the sites. For Wick, $\hat{\beta}_1$ is slightly less than 1, which is indicated by the gradient of the solid line in Figure 6.3 and suggests that the numerical model surge data are slightly too large and need scaling down: this is consistent with Figure 6.1 for the full numerical model data at grid point 1.

The problem with these simple regression fits is that they concentrate on the central portion of the site and overlapping data. i.e. the fitted regression line is dominated by the typical data. It is high values that will dominate high return level estimates and our interest is in re-calibrating the *extremes* of the numerical model data. With this in mind, we consider different forms of regression for the extremes. Our first investigation of this is a censored regression above a threshold. Note that the notation used in this section here is specific to the section and not necessarily consistent with notation from the rest of the report.

Censored regression

With V_t and Y_t denoting the hourly nearest model data and the site data respectively, we fit a

Model I	Estimate	s.e.	t-statc
β_0	-0.002	0.001	0.014
β_4	-0.015	0.0295	0.306
β_2	0.065	0.0581	0.134
β_1	0.767	0.0454	0.001
β_3	0.455	0.0672	0.001
β_5	-0.323	0.0659	0.001
β_6	-0.032	0.0304	0.148
β_7	0.026	0.0318	0.208
$\sigma = 0.00524$	RSS= 28.181	TSS= 148.2	R^2= 81
Model II	Estimate	s.e.	t-statc
β_0	-0.002	0.001	0.014
β_6	-0.028	0.0362	0.218
β_1	0.866	0.0398	0.001
β_3	0.134	0.0126	0.001
$\sigma = 0.00527$	RSS= 28.327	TSS= 148.2	R^2= 81
Model III	Estimate	s.e.	t-statc
β_0	-0.003	0.001	0.007
β_2	-0.096	0.036	0.005
β_1	1.071	0.0352	0.001
$\sigma = 0.00538$	RSS= 28.928	TSS= 148.2	R^2= 80
Model IV	Estimate	s.e.	t-statc
β_0	-0.002	0.001	0.014
β_3	0.837	0.0145	0.001
β_1	0.136	0.0124	0.001
$\sigma = 0.00527$	RSS= 28.331	TSS= 148.2	R^2= 81
Model V	Estimate	s.e.	t-statc
β_0	-0.003	0.001	0.007
β_1	0.979	0.0066	0.001
$\sigma = 0.00539$	RSS= 28.967	TSS= 148.2	R^2= 80

Table 6.1: Summary of regression model fits at Wick. The parameter σ is an estimate of the variance of the regression error variable, ϵ_t. RSS and TSS are the residual and total sum of squares respectively: these measure the fit of the model, with the ratio of the two R^2 being a measure of fit that corresponds to the percentage of the variation in the model that is explained by the regression terms. Broadly, a value close to or much less than 100% with a small number of regression parameters, corresponds to a very good or poor regression model respectively.

linear regression $y = \alpha_u + \beta_u v$ to the points

$$\{(v_t, y_t) : v_t > u\}$$

for a range of thresholds u. The behaviour of the parameter estimates of α_u and β_u as the threshold u is varied, gives an indication of how differently the extremes of the two processes are behaving. Figure 6.5 shows the estimated regression slope parameter β_u for a range of thresholds for some east coast sites. Key features to note from Figure 6.5 are:

- increased uncertainty as the threshold is raised – this results from the reduction in data used to fit the model,
- for most sites the slope estimate changes at the extremes – increasing for North Shields, Whitby and Immingham, decreasing for Wick, Aberdeen, Leith and Cromer, and remaining constant for Lowestoft,
- a decrease/increase in estimates corresponds to the numerical model overpredicting/underpredicting extreme surges relative to typical surges.

Quantile regression

For each site and overlapping numerical model data, estimates of the $91, 92, \ldots, 99\%$ quantiles are obtained empirically: these are shown on Figures 6.3-6.4 to be linearly related. We denote these quantile estimates by $q_{site}(i)$, and $q_{num}(i), i = 1, \ldots, 9$, and fit the linear model

$$q_{site} = \alpha + \beta q_{num} + \epsilon \tag{6.2.3}$$

where α and β are intercept and scale parameters for this model. Figures 6.3–6.4 displays the results for all sites: the crosses on figure represent estimated quantiles (i.e. $\{(q_{site}(i), q_{num}(i)) : i = 1, \ldots, 10\}$) plotted against estimated quantiles obtained from overlapping data. The dotted line is a fitted regression line to the derived quantile data. The solid and broken lines are the line $y = x$ and the regression line from fitting the censored regression model respectively. The general pattern is that the site data has higher quantiles than the numerical model data. Only the short record sites (not shown) of Newhaven and Workington have lower quantiles than their nearest grid point data. The differences appear largest at sites such as Felixstowe, Newport, and Mumbles. In general the standard regression differs significantly from the quantile regression, for example at Aberdeen. Also, the slope estimates seem to be less than one for the east coast and greater than one for all other coasts.

The striking feature of these plots is the linearity in the quantile-quantile lines. This linearity, in the range 91-99%, gives us confidence in extrapolating the transformation to higher levels than the 99% quantile.

Comparisons

Although the censored regression results show that the extremes do not behave too differently, there are enough differences to suggest that a regression on all the data is not appropriate. The linearity in the quantile plots suggests that this type of transformation is a simple and effective way of calibrating the extremes of the numerical model data. Thus we use the quantile regression approach to calibrate the data in this section.

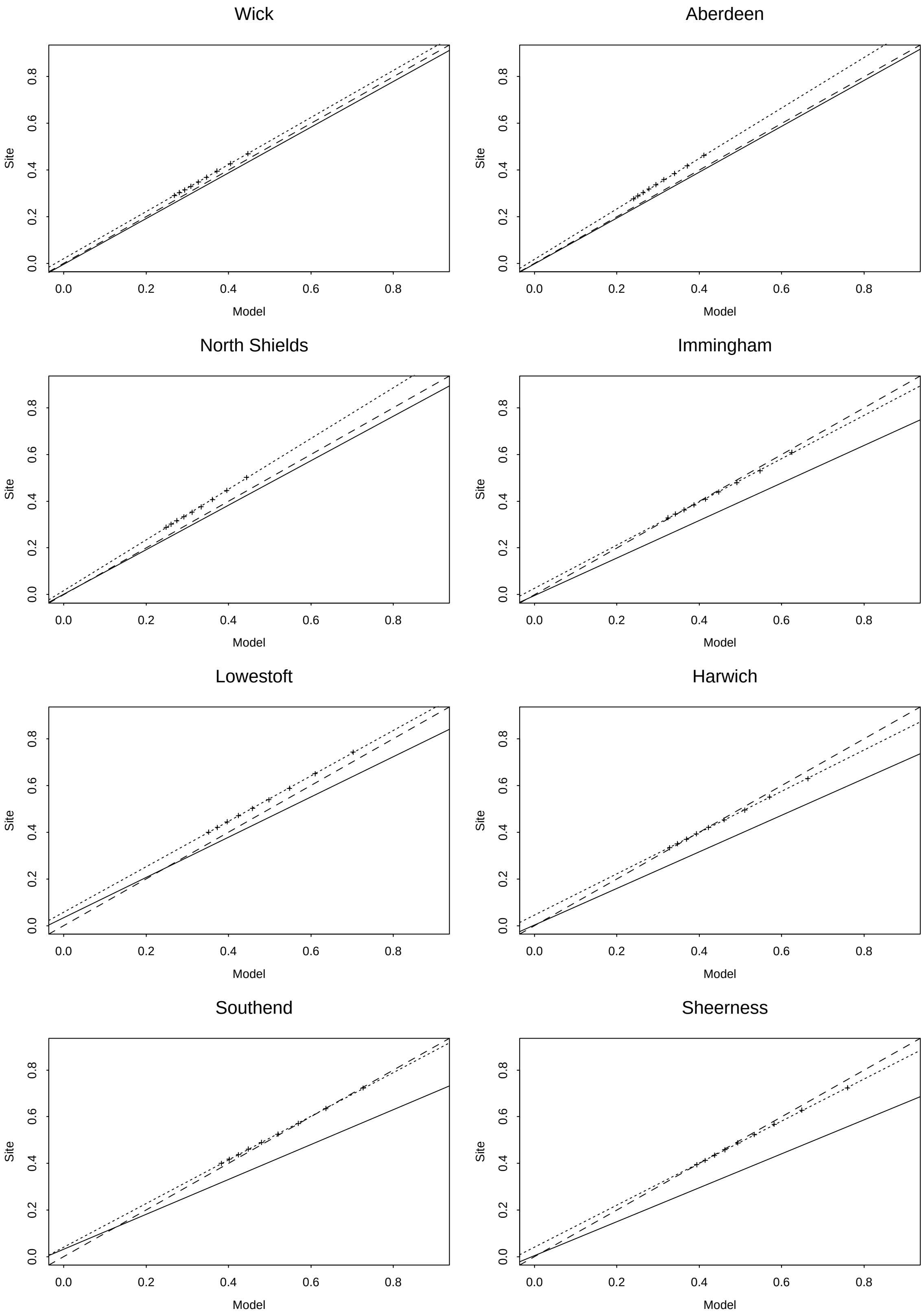

Figure 6.3: Regression lines obtained from fitting (1) standard linear regression to site data against nearest grid point (solid line), (2) from 91,92,...,99 % estimated quantiles from each location for Wick to Sheerness. (dotted line). (3) Site equals to model reference line (broken line)

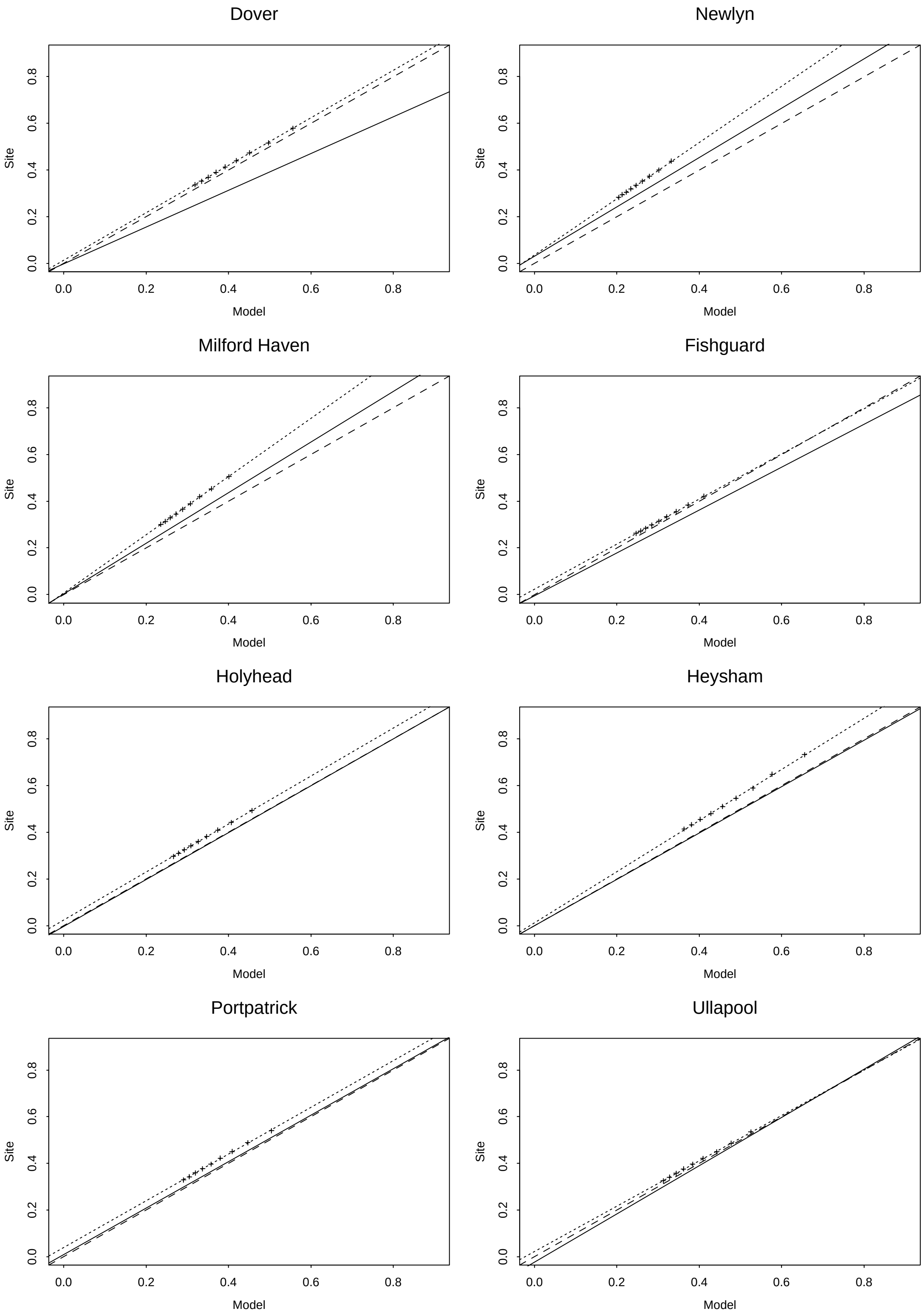

Figure 6.4: Regression lines obtained from fitting (1) standard linear regression to site data against nearest grid point (solid line), (2) from 91,92,...,99 % estimated quantiles from each location for Dover to Ullapool. (dotted line). (3) Site equals to model reference line (broken line)

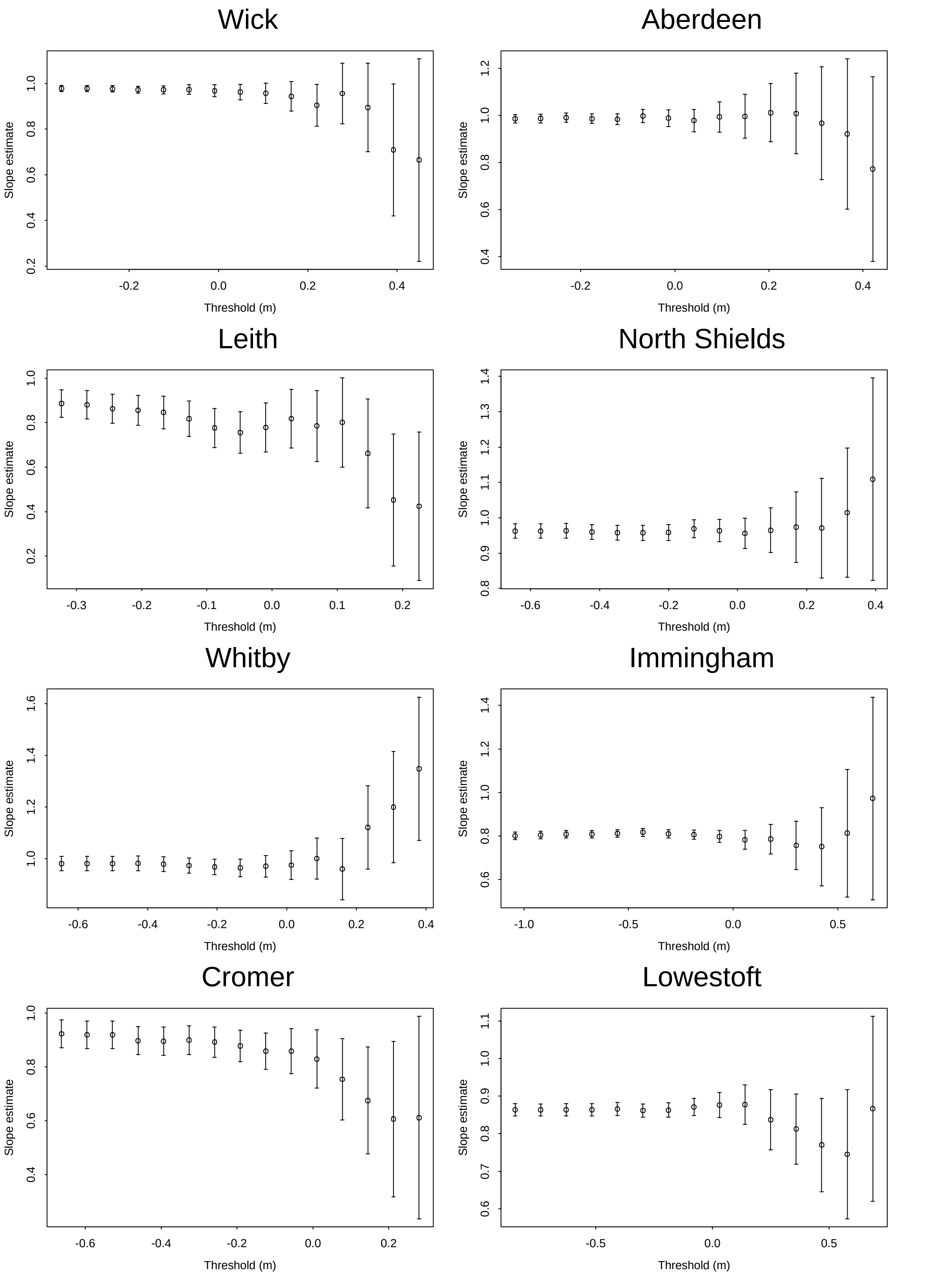

Figure 6.5: Regression slope estimates of site data against overlapping numerical model data conditional on a threshold on the numerical model data.

6.2.2 Spatial calibration

The intercept and slope parameter estimates from the quantile regression model provide a way of calibrating the numerical model data at grid points nearest to the sites. In order to extend this to be applicable at all grid points around the coast, we obtain a spatial estimate of each calibration parameter, by smoothing the site-estimates with distance, and then use this spatial estimate to give an adjustment factor around the entire coast. Figure 6.6 shows the estimates of the intercept and slope for every site. Sites with long data records are labelled by an abbreviation, and shorter record sites are indicated by a single point. The spatial estimate, shown as a solid line, is a weighted kernel regression smoother against distance. The graph wraps around so that Wick has distances of 0 and 4873km. The spatial estimate of the intercept is always positive and approximately constant at 0.03 for the whole coast. The scale estimate has little more structure with large values in the regions from the South to the North-West. Recall that a slope value of greater than, and less than, one corresponds to the numerical model data underestimating, and overestimating, the site data respectively.

6.2.3 Fitting the SRJPM

The spatial estimates of the location and scale adjustment parameters in Figure 6.6 provide a way of calibrating all of the numerical model data. Once this calibration has been applied, the SRJPM can be applied at every grid point to the adjusted data. Before comparing the resulting return level estimates, we concentrate on the surge and examine the constituent components of the SRJPM as estimated from

- the site data
- the overlapping grid point data (adjusted)
- the full grid point data (adjusted)

as in the empirical investigation of Chapter 2. The relevant parameters of the surge component of the SRJPM are the empirical conditional distribution of surge given tide, the interaction functions, the extreme surge parameters and the extremal indices. For illustration we only show a subset of the results for the high-tide a-function and the GEV scale and shape parameters. Figures 6.7, 6.8, and 6.9 display these parameters as estimated from the three data types above. On these figures, the small faint site name abbreviations represent the site data, the large bold names represent the nearest grid point overlap data and the solid line joins the full, adjusted, numerical model based estimates to produce the spatial estimate of each parameter. Note there is a slight abuse of graphical notation here, as the site abbreviations may have different distances for the same site, since they represent the nearest grid point distance. Key features to note about the three estimates are:

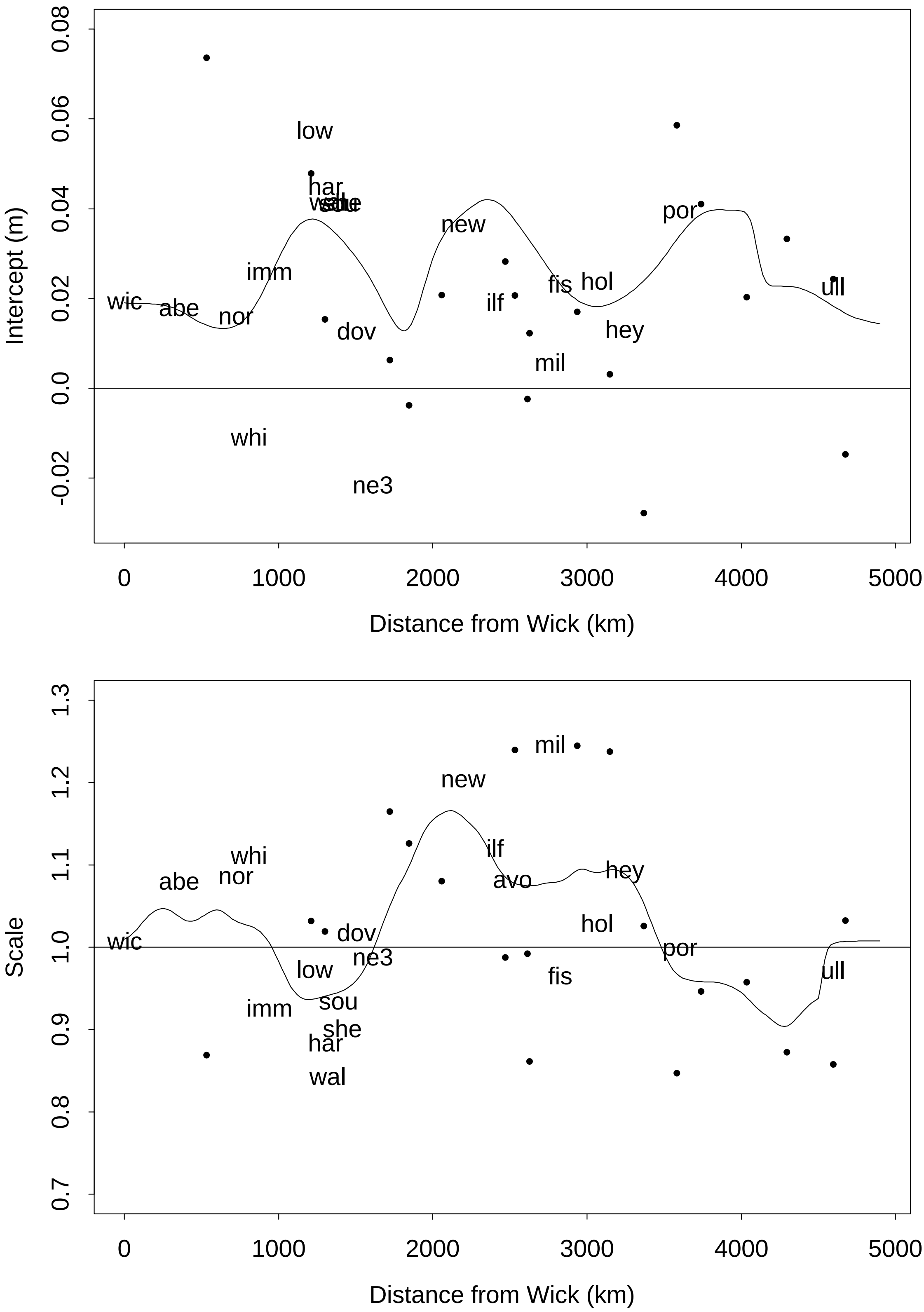

Figure 6.6: Spatial and site-by-site estimates of the location and scale adjustments. The estimates are obtained by fitting a linear regression to estimated top quantiles for the site and the numerical model data at the nearest grid point to the site.

- differences in estimates are larger between the site and full numerical model estimates than between the overlap and full numerical model estimates.

- Given the confidence intervals, the agreement is generally good, with the spatial estimate producing tighter confidence intervals and a physically based spatial mapping.

In the order shown, the plots show:
a-function
As expected, the scaled interaction function at high tide is below 1 for most of the UK which corresponds to a dampening of the surge at high tide levels. There seems to be little evidence for sampling bias except for Devonport and Millport, where the overlap and site estimates agree but the full numerical model estimate is poor.
Scale parameter
The scale parameter varies smoothly over the UK coast ranging from minimum levels at Wick to maximum levels in the Bristol Channel. Generally though it is slowly changing over long distances. Features to note about the three estimates are:

- Weymouth overlap and full numerical model data are quite different–with the full data estimate being much more consistent with estimates from neighbouring sites and grid points.

- Newlyn and Milford Haven have good agreement–with between site and overlapping data but the full model data gives different estimates which suggests possibly atypical observational data for this parameter at these sites.

- confidence intervals are small relative to the spatial variation in this parameter.

Shape parameter
The shape parameter generally lies between 0 and 0.2. It is approximately constant along coastlines; $k = 0.2$ for the east coast, $k = 0$ for the south coast, and $k = 0.2$ again around the north west coast. The site and overlap estimates agree well for longer sites. Note that a larger shape parameter corresponds to a shorter tail in the estimated GEV distribution.

6.2.4 Return level estimation

Finally Figures 6.10 and 6.11 show the return level estimates from **Approach II**. Generally the estimates from **Approach II** agree better with the site estimates, and the UK east coast spatial estimates, than **Approach I** estimates. Notable improvements are at Wick and Immingham but estimates for Southend and Sheerness are slightly worse. None of the other estimates is much changed from **Approach I**.

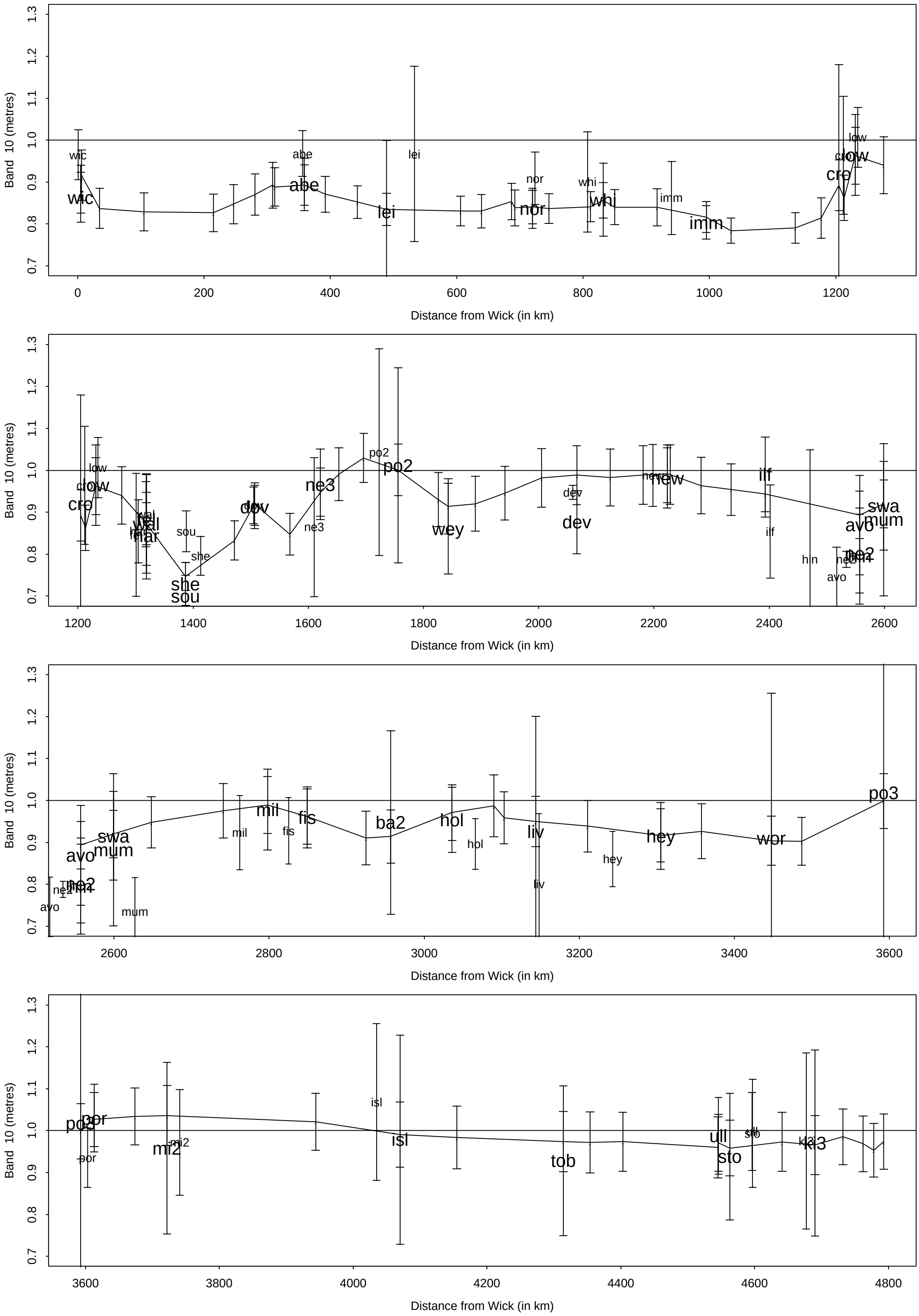

Figure 6.7: Estimates of the interaction function, $a()$ in the top tidal band, for three data sets. The continuous line interpolates estimates from the full numerical model data from each grid point. The small faint site names are the estimates obtained from the site data, and the large bold names are the estimates obtained from overlapping data from the grid point nearest the site.

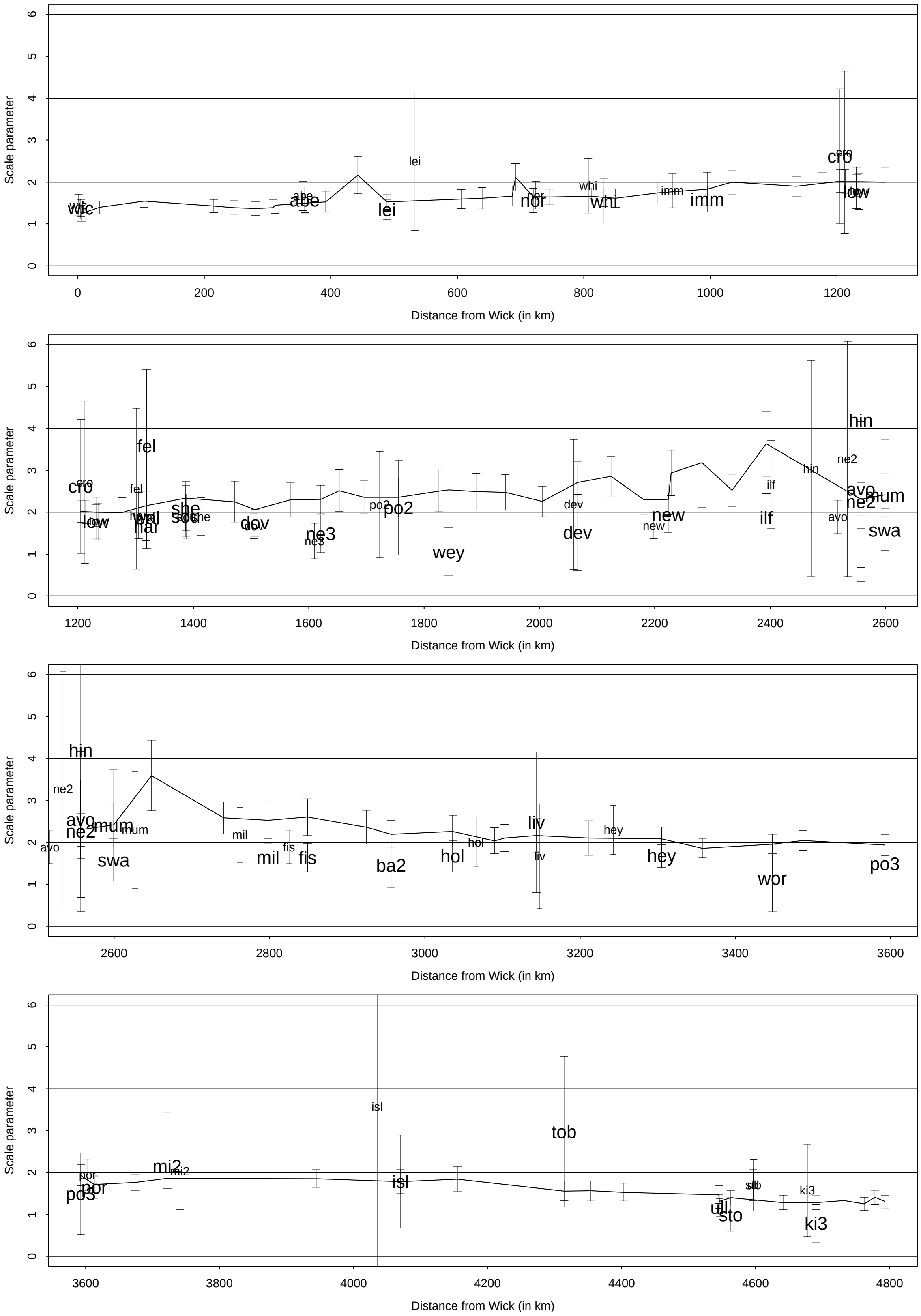

Figure 6.8: Estimates of the scale parameter for three data sets. The continuous line interpolates estimates from the full numerical model data from each grid point. The small faint site names are the estimates obtained from the site data, and the large bold names are the estimates obtained from overlapping data from the grid point nearest the site.

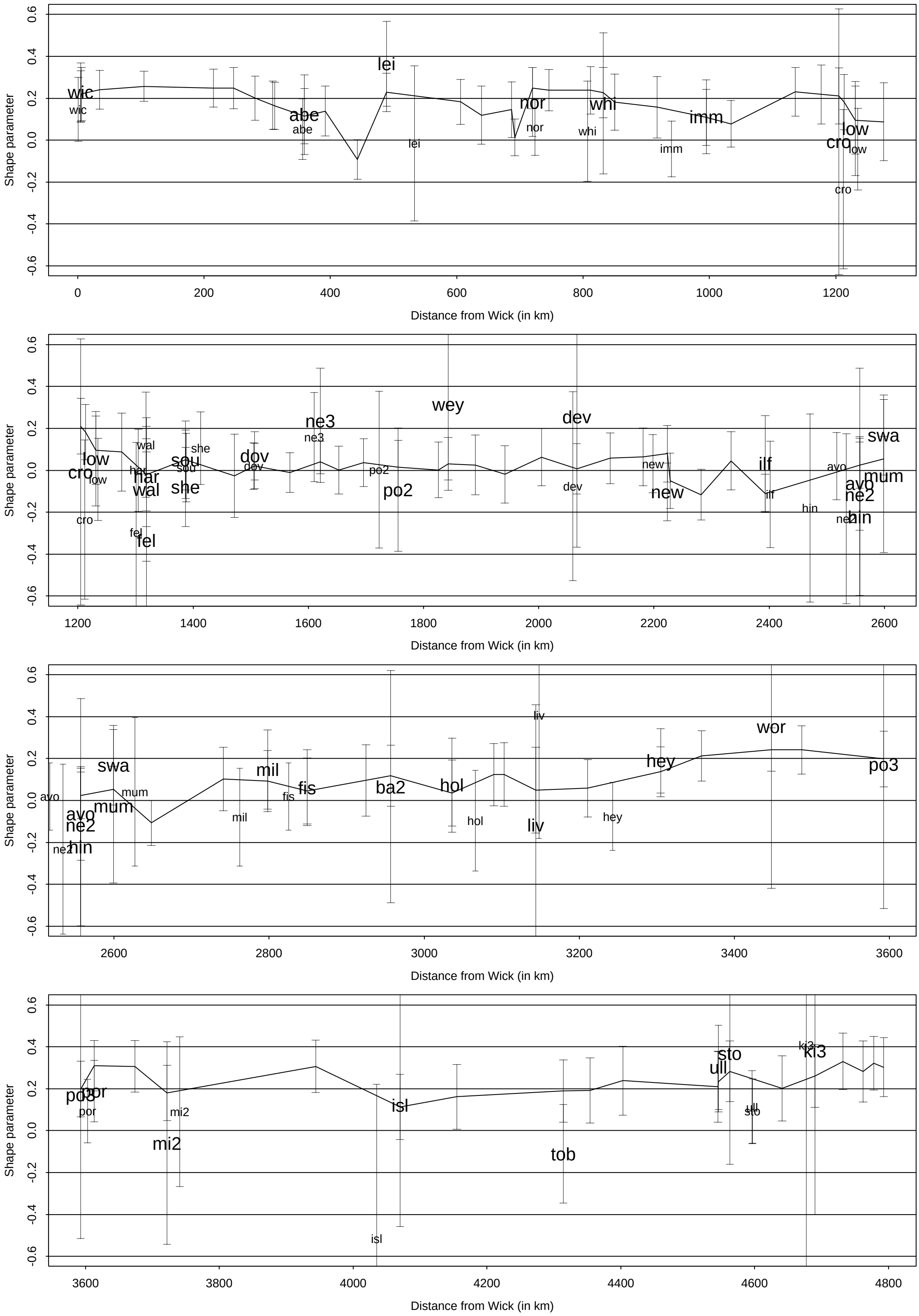

Figure 6.9: Estimates of the shape parameter for three data sets. The continuous line interpolates estimates from the full numerical model data from each grid point. The small faint site names are the estimates obtained from the site data, and the large bold names are the estimates obtained from overlapping data from the grid point nearest the site.

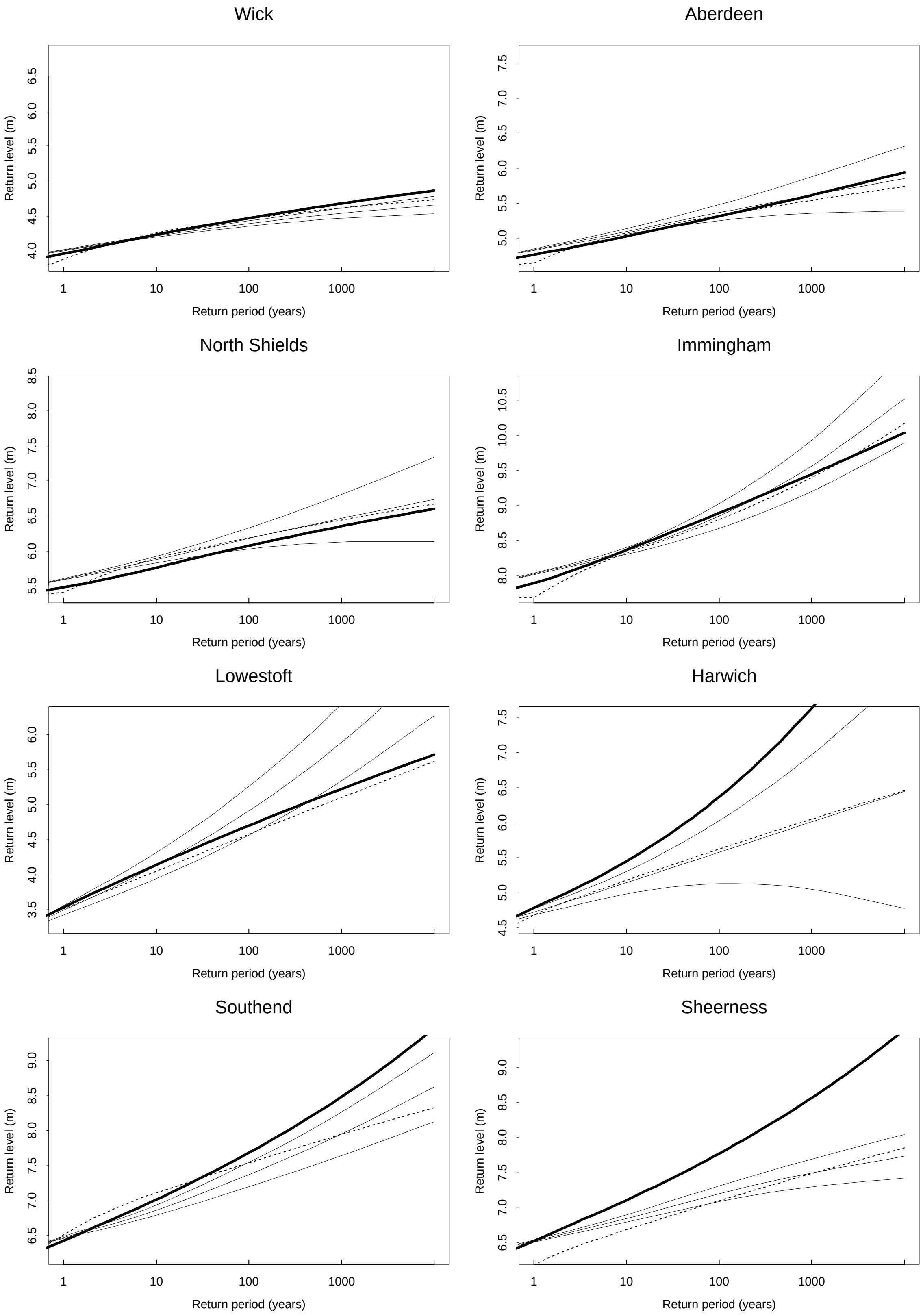

Figure 6.10: Port diagrams at the sites for **Approach II**. The bold lines are for **Approach II**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

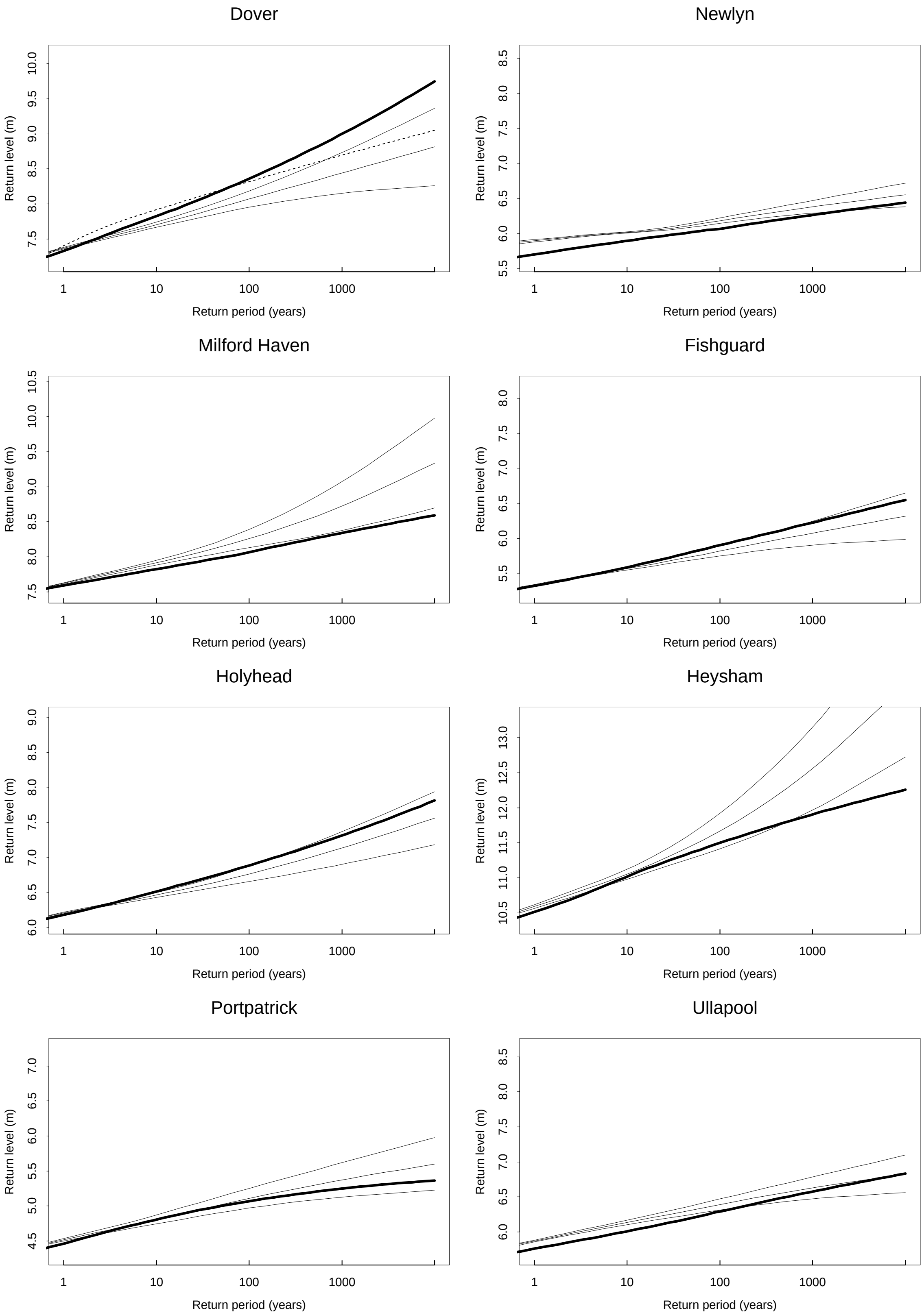

Figure 6.11: Port diagrams at the sites for **Approach II**. The bold lines are for **Approach II**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

6.3 Approach III: Return level calibration

First we apply the SRJPM to the three data sets

- site data
- overlapping grid point data, and
- full grid point data.

Return level estimates are obtained, from the SRJPM, for each of the data sets. Corrected return levels at each grid point are then obtained by adjusting the return level obtained from the full grid point data at each grid point. The return levels are adjusted according to the following procedure which corrects for sampling bias in the observational data and discrepancy between observational and numerical model data.

Define the return level at a site to be $\hat{z}_p$, and at the nearest grid point, for the overlapping data, to be $\hat{v}_p$. Next compute differences $\hat{z}_p - \hat{v}_p$ for a range of values of p between 0.1 and 0.0001. In other words we form the difference between the port diagram curves, obtained by the SRJPM, at the site and the nearest overlapping grid point. These differences are plotted, as solid dots, against $-\log(-\log(1-p)) - 2$ in Figures 6.12 and 6.13 for each site. If the site and nearest grid overlapping data have identical return level estimates, then the differences lie along the line $y = 0$. Our aim is to obtain an adjustment factor, which, when applied to the nearest model return level estimates, makes the site and nearest grid estimates match up. In other words we wish to correct the $\hat{v}_p$ for any differences, that may be due to biases in the numerical model data.

To do this, we fit both a linear and a quadratic regression model to the differences. Specifically, taking 39 values of $p : p_1, \ldots, p_{39}$, we fit a linear (and quadratic) model to the points $(\hat{z}_{p_i} - \hat{v}_{p_i}, p_i : i = 1, \ldots, 39)$. The fitted linear and quadratic models are shown on Figures 6.12 and 6.13 as solid lines. The quadratic fit appears to be substantially superior at the expense of one extra parameter, for most sites, and this is used in the following analyses.

To produce calibration factors for the whole coastline, the location, scale and quadratic parameters are smoothed with distance. The resulting spatial estimate is shown for each parameter in Figure 6.14.

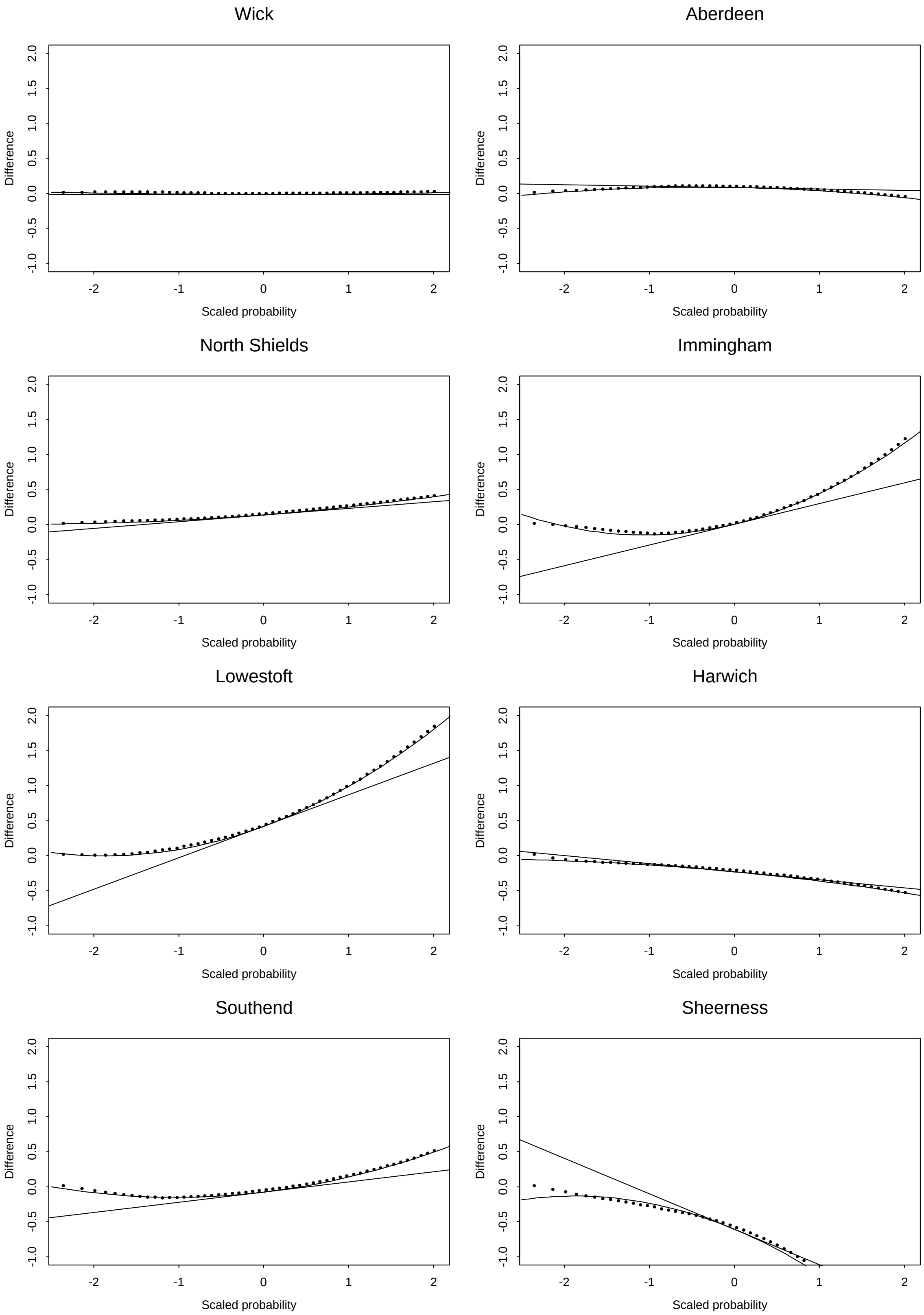

Figure 6.12: Regression fits at each site for the return level adjustment factors. The plots show the difference between site estimated return levels, and nearest grid point return levels plotted against scaled probability, which is -log(-log(1-p))-2. The dots are observed differences and the continuous lines are the fitted linear and quadratic regression lines.

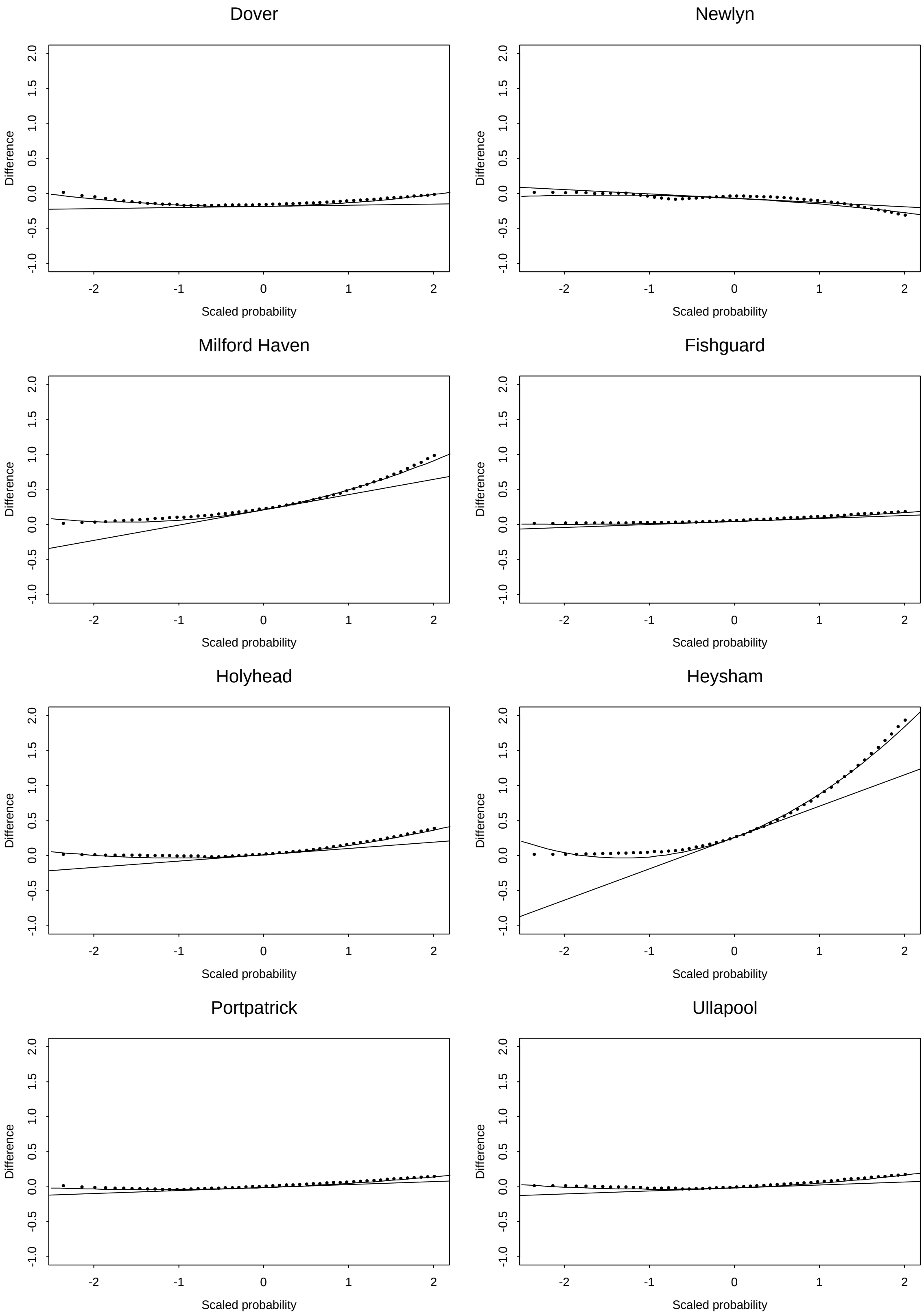

Figure 6.13: Regression fits at each site for the return level adjustment factors. The plots show the difference between site estimated return levels, and nearest grid point return levels plotted against scaled probability, which is -log(-log(1-p))-2. The dots are observed differences and the continuous lines are the fitted linear and quadratic regression lines.

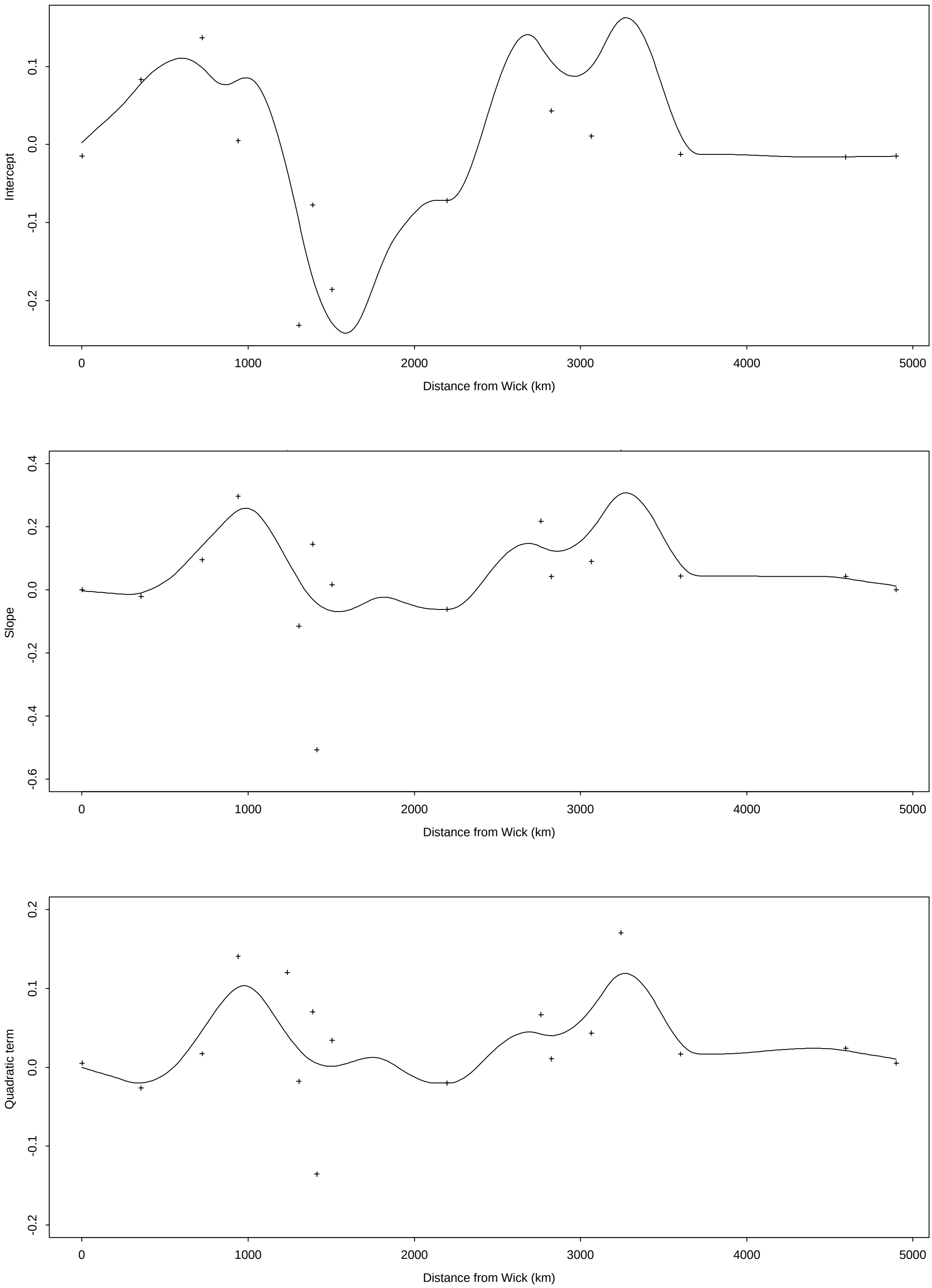

Figure 6.14: Spatial estimates of the return level adjustment factors for use in **Approach III**.

6.3.1 Return level estimation

The adjustments are applied to return levels obtained from the full numerical model data, and this gives return levels at every grid point. Figures 6.15 and 6.16 show the estimated return levels under **Approach III** as port diagram curves. Relative to **Approach I**, these are slightly better at Immingham, Southend, Sheerness, Dover, Milford, and Heysham, but are worse at Newlyn, Fishguard and Holyhead.

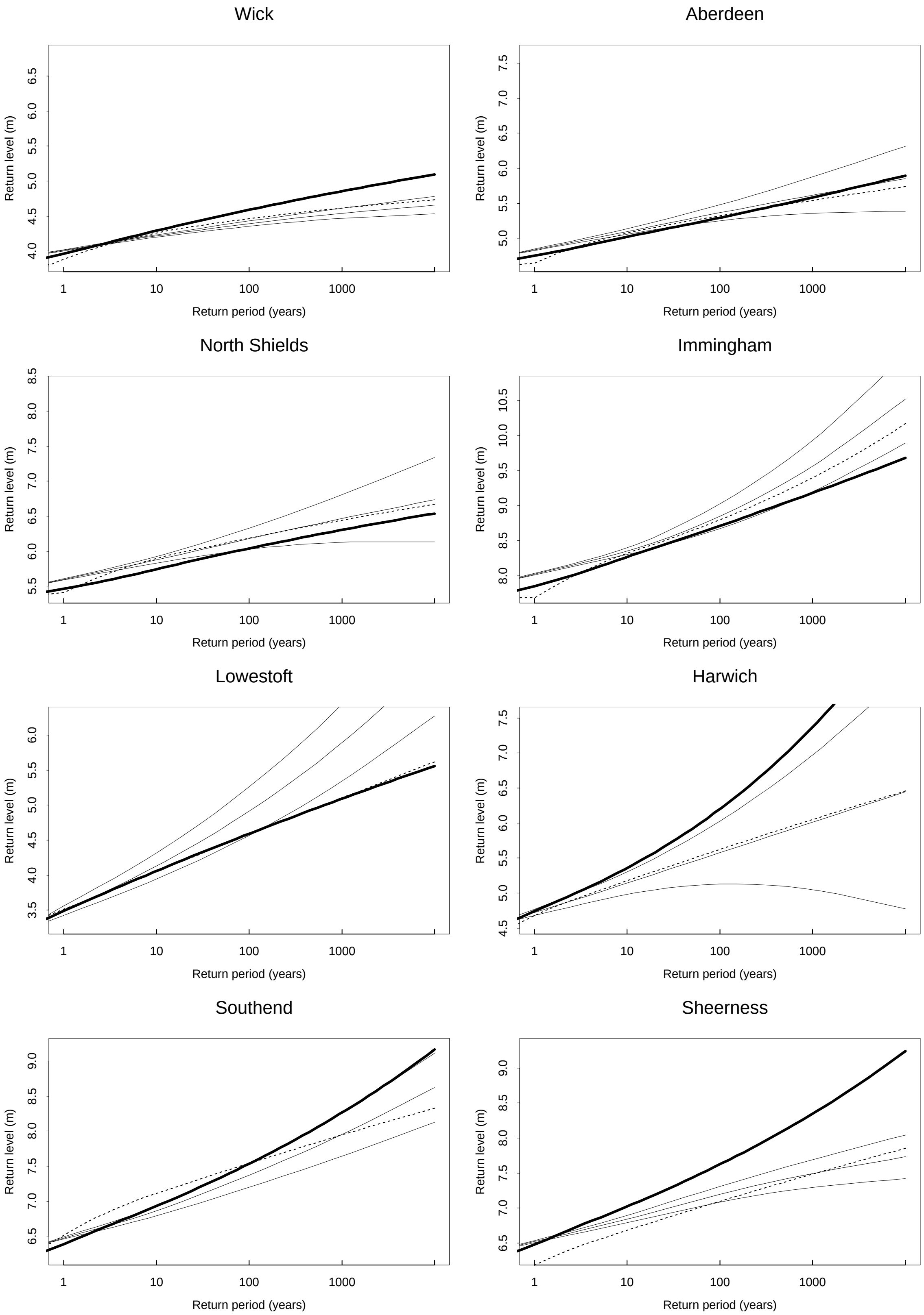

Figure 6.15: Port diagrams at the sites for **Approach III**. The bold lines are for **Approach III**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

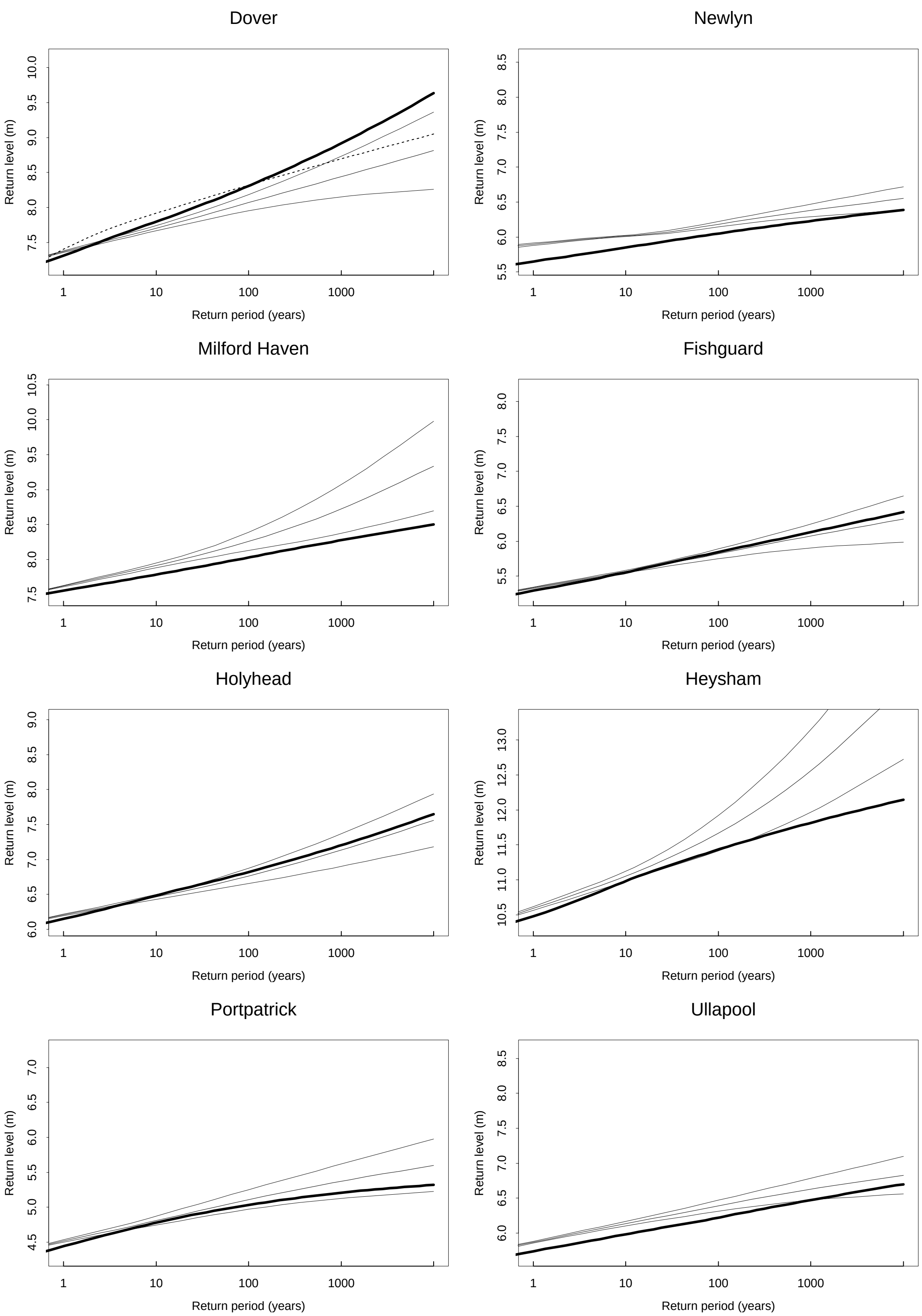

Figure 6.16: Port diagrams at the sites for **Approach III**. The bold lines are for **Approach III**. Site values are faint continuous lines, showing 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

Chapter 7

Approach IV: Parameter Calibration

The motivation behind the development of the SRJPM in DT2 was to provide spatial return level estimates along the east coast. This was achieved by separating the SRJPM into its component parts, spatially smoothing these, and re-combining the spatial estimates. This approach worked well for the east coast site data. An extension of this method, which enables numerical model data to be incorporated, is examined in this chapter.

The initial step is to apply the SRJPM to the 3 data types of

- the site data
- the overlapping grid point data, and
- the full grid point data.

This gives estimates of each SRJPM constituent parameter from the three data types. The procedure is then to spatially estimate each of the constituent parameters using information from these three estimates. As in DT2, we assume independence between the constituent parameters so that we can consider each parameter separately.

First we describe the method used to spatially estimate each parameter. Assume we wish to obtain a spatial estimate of some parameter $\phi(d)$ for each distance d. Define the estimates of the parameter at

- the ith site by $\hat{\phi}_{site}(d_i)$
- the nearest grid point overlap data to site i, by $\hat{\phi}_{near}(d_i)$,
- the numerical model full data at grid point j by $\hat{\phi}_{num}(s_j)$,

for $i = 1, \ldots, n_s$ and $j = 1, \ldots, n_g$ where d_i is the distance of site i, and s_j is the distance of grid point j and n_s and n_g are the number of sites and grid points respectively. Also let the number of years of data at site i be n_i. The parameter ϕ, at distance d, $\phi(d)$, is then estimated according the following algorithm.

First we compute the sequence of differences

$$\epsilon(d_i) = \hat{\phi}_{site}(d_i) - \hat{\phi}_{near}(d_i), i = 1, \ldots, n_s,$$

which measures the error in the numerical model data in estimating ϕ at d_i. Next we apply a weighted kernel regression estimate to the points $\{d_i, (\epsilon(d_i)) : i = 1, \ldots, n_s\}$. The weights are proportional to the length of data, n_i at each site. This gives a spatial estimate of differences, $\hat{\epsilon}(d)$, for all distances d around the coast. The adjusted estimate of the parameter at each grid point j, $\hat{\phi}(s_j)$ is then obtained by

$$\hat{\phi}(s_j) = \hat{\phi}_{num}(s_j) + \hat{\epsilon}(s_j)$$

Finally, $\hat{\phi}(d)$ is obtained at any distance d by interpolating the $\hat{\phi}(s_j)$ estimates.

This procedure gives an adjusted estimate $\hat{\phi}(d)$ for each parameter $\phi(d)$ at each distance d. At each grid point, each of the adjusted parameter estimates are then recombined within the SRJPM to give an estimate of the return level. Note that:

- $\hat{\epsilon}(s_j)$ =0 if the overlapping data gives the same estimate as the site data. The $\hat{\phi}$ will be $\hat{\phi}_{num}$ which can be quite different from $\hat{\phi}_{site}$ if there is sampling bias.

- If $\hat{\phi}_{num} = \hat{\phi}_{near}$ then $\hat{\phi} = \hat{\phi}_{site}$ if this pattern is reflected at neighbouring sites.

Before we display the results for a sample subset of the parameters, we illustrate the above process in detail by application to the GEV shape parameter in the SRJPM. Figure 7.1 shows each of the estimates $\hat{\phi}_{site}(d_i)$, $\hat{\phi}_{near}(d_i)$, and $\hat{\phi}_{num}(s_j)$ plotted against distance. For example at Wick, $\hat{\phi}_{site}$ is similar to $\hat{\phi}_{num}$, but is lower than $\hat{\phi}_{near}$. Thus there appears to be a slight positive bias in the numerical model data near Wick, and $\epsilon(d_1)$ is approximately -0.08. Figure 7.2 gives $\epsilon(d_i)$ at each site, and the corresponding spatial estimate $\epsilon(d)$ plotted against distance. Finally, Figure 7.3 gives $\hat{\phi}(d)$ plotted against distance. The site estimates are also given on this figure.

The remainder of this section is a discussion of the figures that follow for each parameter and the resulting return levels.

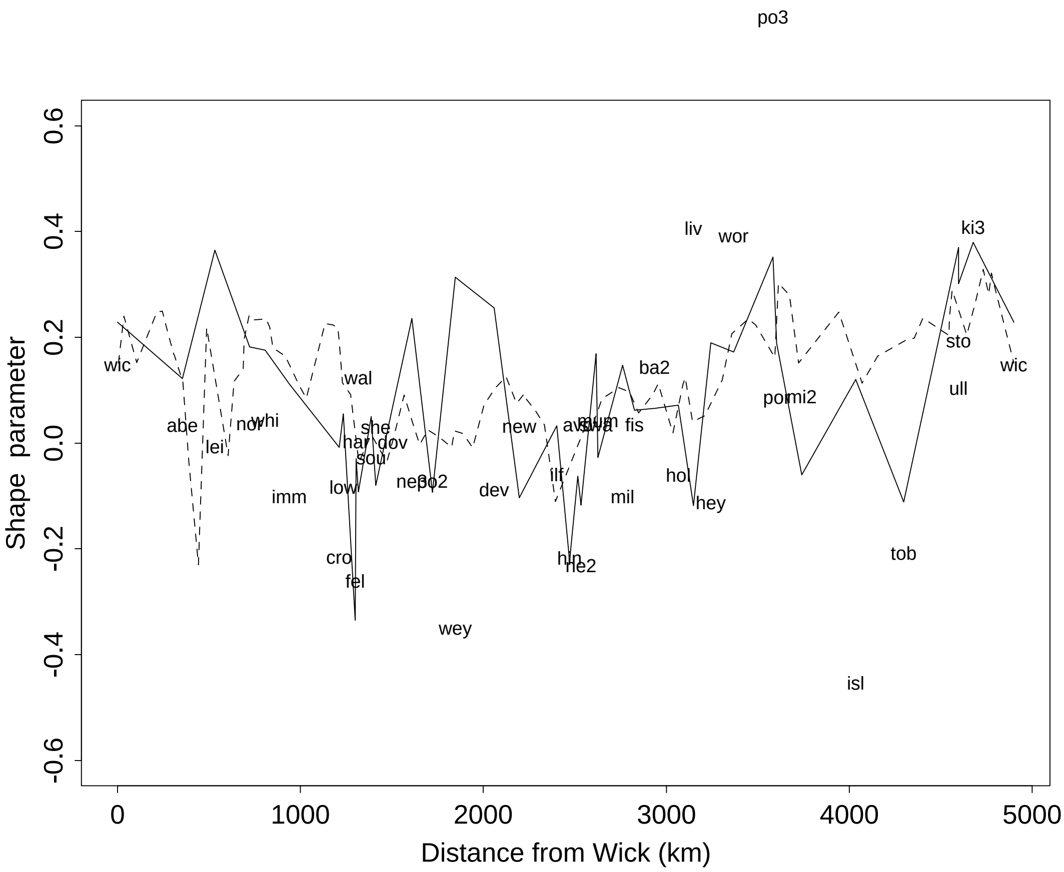

Figure 7.1: Spatial estimate of the shape parameter. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site.

7.1 Interaction functions

Figure 7.4 (a)-(c) show the unscaled a functions plotted against distance. The solid line corresponds to linearly interpolated ϕ_{near} estimates, i.e. the unadjusted overlapping data. The broken line is obtained from the full raw grid point data. The site names are the site estimates. In general ϕ_{near} matches the site estimates well. If the solid line and sites agree well but the broken line differs, then this suggests that the sampling period of the site data is unrepresentative and in these cases substantial improvements may be obtained by including numerical model data. This tends to happen at short data sites; for example Devonport, Tobermory, Kinlochbervie, and Ullapool. Figure 7.5 shows the spatial estimate of the a-functions plotted against distance. This estimate is obtained by adding smooth differences between the solid line and site estimates to the dotted line in Figure 7.4. The resulting curve agrees well with site estimates apart from at south coast sites with short records. Note the improvement the parameter calibration is giving

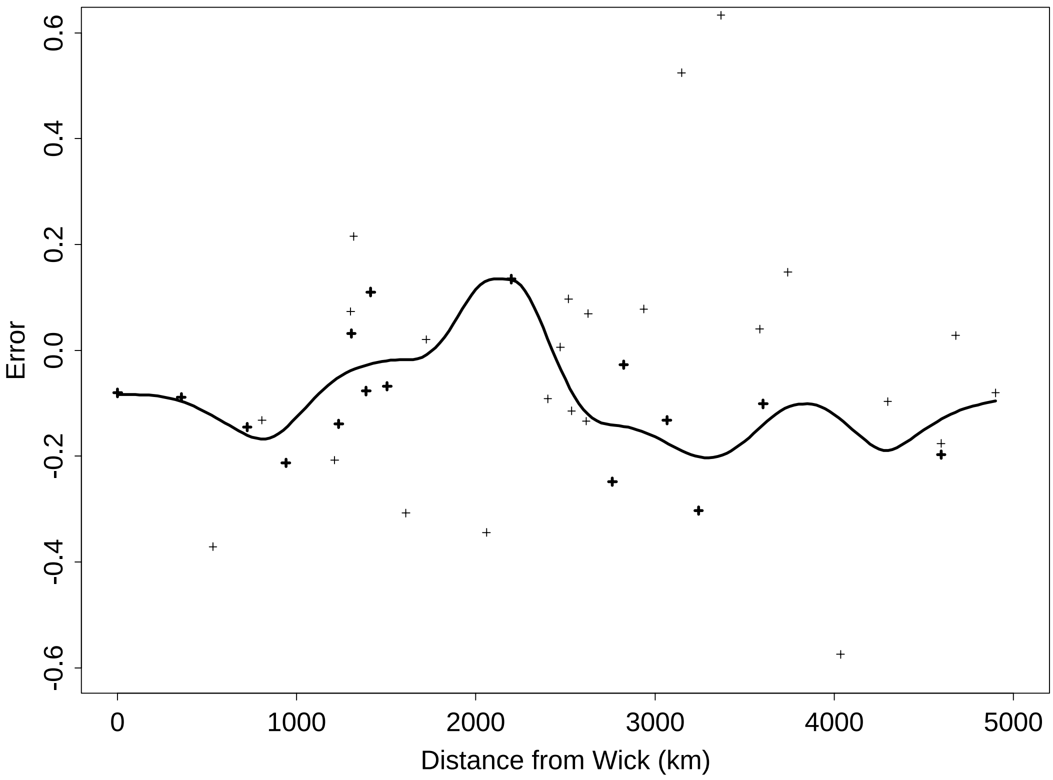

Figure 7.2: Spatial estimate of the shape parameter adjustment. The solid line is the spatial kernel regression estimate, and the points are the site-estimates. For clarity, the long data sites, which have most influence on smoothing are given as heavy points.

at sites where the two numerical model estimates agree but are different from a long record site estimate. For example, see Aberdeen and Lowestoft in the top tidal band plot. The resulting estimate for these sites is in closer agreement with the site estimates than the numerical model estimates.

7.2 GEV parameters

Figures 7.6-7.10 and Figure 7.1 show the GEV parameters functions plotted against distance. As in the previous section, the solid line corresponds to linearly interpolated ϕ_{near} estimates, and the broken line is obtained from the full raw grid point data. Again, in general ϕ_{near} matches the site estimates well. Unrepresentative sampling periods can be seen at sites:

- Wick, Aberdeen, and Leith in terms of the location parameter,

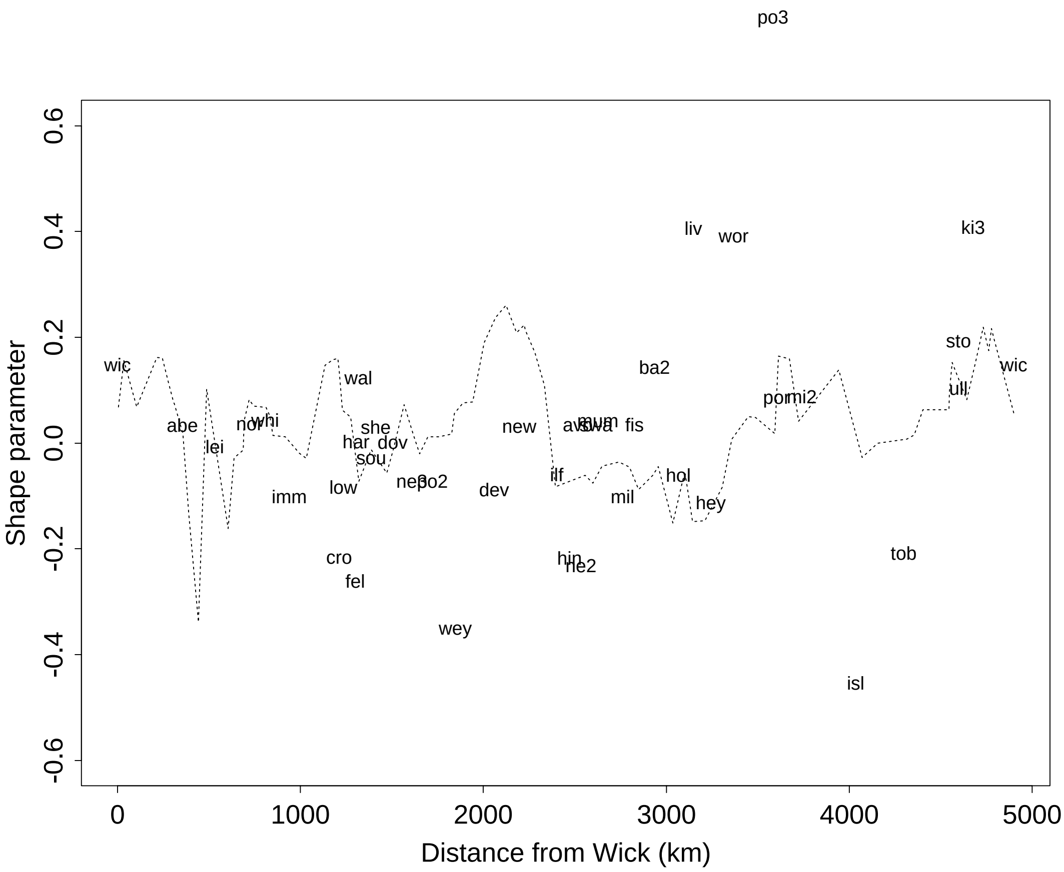

Figure 7.3: Spatial estimate of the shape parameter given by the broken line and obtained by **Approach IV**. Site estimates are indicated by site abbreviations.

- Newlyn in terms of the scale parameter,
- Heysham for the shape parameter. Other sites where there appears to be unrepresentative sampling periods in terms of the shape parameter estimates, are Cromer, Lowestoft, Felixstowe, Newhaven, Portsmouth, Hinkley, Heysham, and Portpatrick.
- Tobermory for all parameters,

DT2 find that the shape parameter varies smoothly along the coastline. Thus we apply a smoothing to the raw spatial estimate, and the raw and smoothed estimate are shown by the dashed line and the heavy solid line respectively in Figure 7.10.

7.3 Return levels at the sites

Figures 7.11–7.14 give port diagrams for site-by-site comparisons. The figures are similar to those in the comparisons of the first three methods, but here we present comparisons for all the

A-class sites. The general pattern is that the spatial estimates match the site estimates well. Some points of interest from these figures are:

- By comparison with **Approach I** there is improved agreement with the site estimates for North Shields, Whitby, Immingham, Harwich, Walton, Southend, Sheerness, Newlyn, Holyhead, and Heysham.

- There is worse agreement at Avonmouth, Fishguard and Stornoway.

- The short record sites, previously omitted, have sensible estimates provided by **Approach IV** by comparison with the site estimates. On the east coast, Cromer and Felixstowe have estimates which are similar to the DT2 spatial estimates. On the south and west coasts, DT2 did not develop spatial estimates, so in these cases, **Approach IV** corresponds to the first spatial estimate from hourly data. The spatial estimate appears to be significantly different to the site estimates for Newhaven and Portsmouth which is probably due to the confidence intervals being too tight at the sites (a feature which occurs at some short record sites). For other short record sites, such as Swansea, Mumbles, and Millport, the spatial estimate agrees well with the site estimates. Finally, for Newport the completely unrealistic estimate provided by the hourly data site estimate is dramatically improved by the **Approach IV** estimate, which is consistent with estimates from historical annual maximum data (see Coles and Tawn, 1990).

- **Approach IV** gives a different estimate from the site and east coast for Wick. The most likely reason for this is the sampling bias at Wick which resulted in the data from Wick missing the larger storm surge events. Correspondingly, the **Approach IV** return level estimates are higher than the site estimates. As Wick was the end site of the east coast analysis and far from other sites, this bias was not detected in the previous spatial analysis.

- Lowestoft also has a discrepancy between the site and **Approach IV** estimates, but there the east coast estimate agrees with **Approach IV**. This suggests biased sampling which is corrected for by any spatial analysis due to the dense network of sites in this coastal region.

A final and important feature to note is that **Approach IV** tends to underestimate relative to the site estimates up to the 20 year return periods. This is particularly noticeable at North Shields, Immingham, Southend, Newlyn, and Ullapool. This feature arises as we do not adjust the empirical distribution of surges conditional on tides below the extreme surge threshold level, so here the raw numerical model data are used. This feature only influences short period return levels, as long periods extreme sea-levels can only occur due to an extreme surge in combination with an extreme tide. This feature is apparent in **Approach I** and is partially removed in

Approach II. **Approach III** largely removes this problem, but at a cost (see Section 7.4). At these data sites, the feature can be removed by using the empirical distribution of the site surges instead of the numerical model surges. However, there would then be no basis for spatial mapping to intermediate site. Given that the order of error appears to be at most 0.25m, and negligible at most sites, we make no efforts to remove this feature here.

Finally, Table 7.1 gives the return level estimates at the sites using the site-tides, as in Figures 7.11–7.14

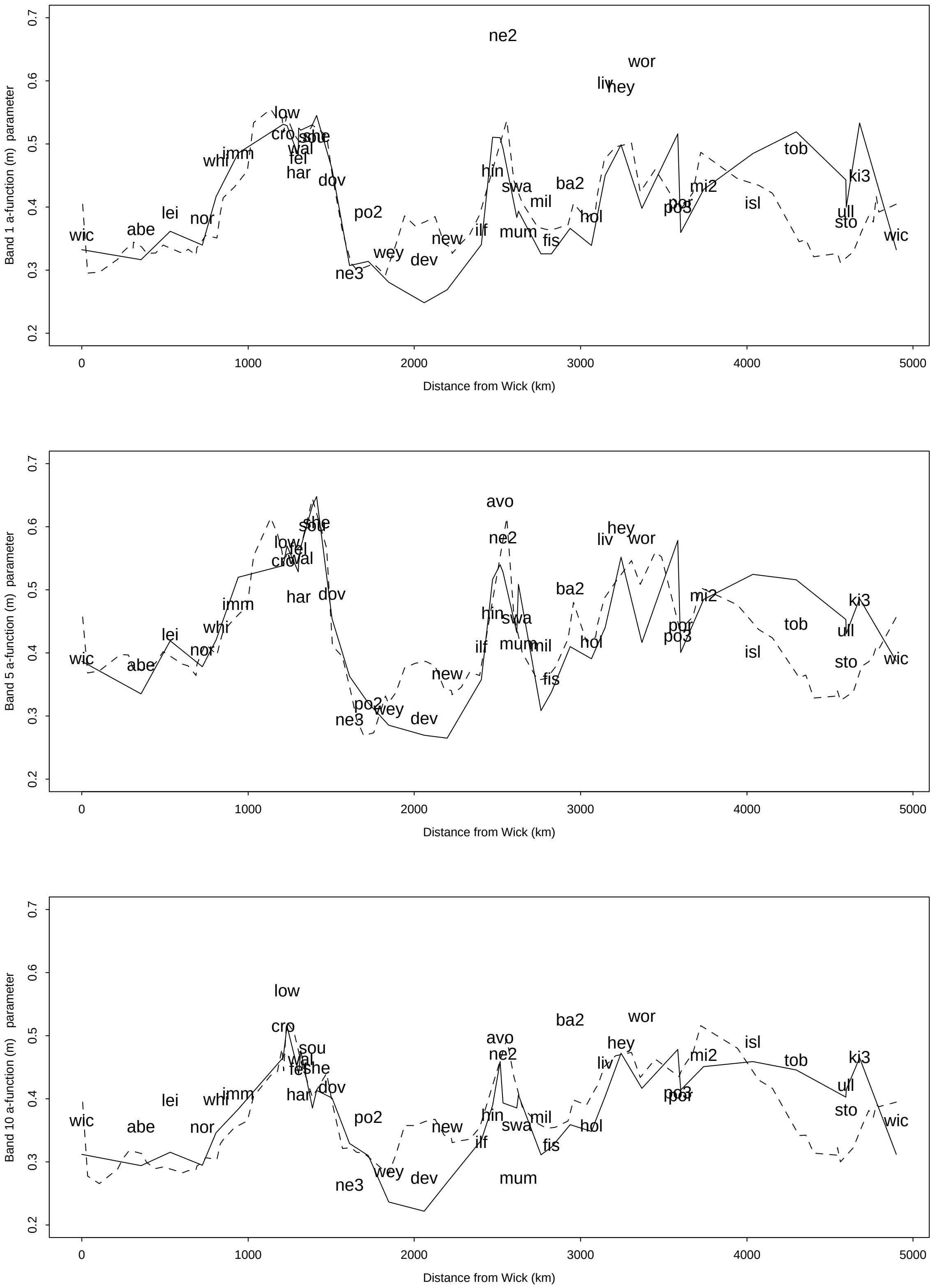

Figure 7.4: Spatial estimate of the interaction a-function for low, mid and high tides in unscaled form. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site.

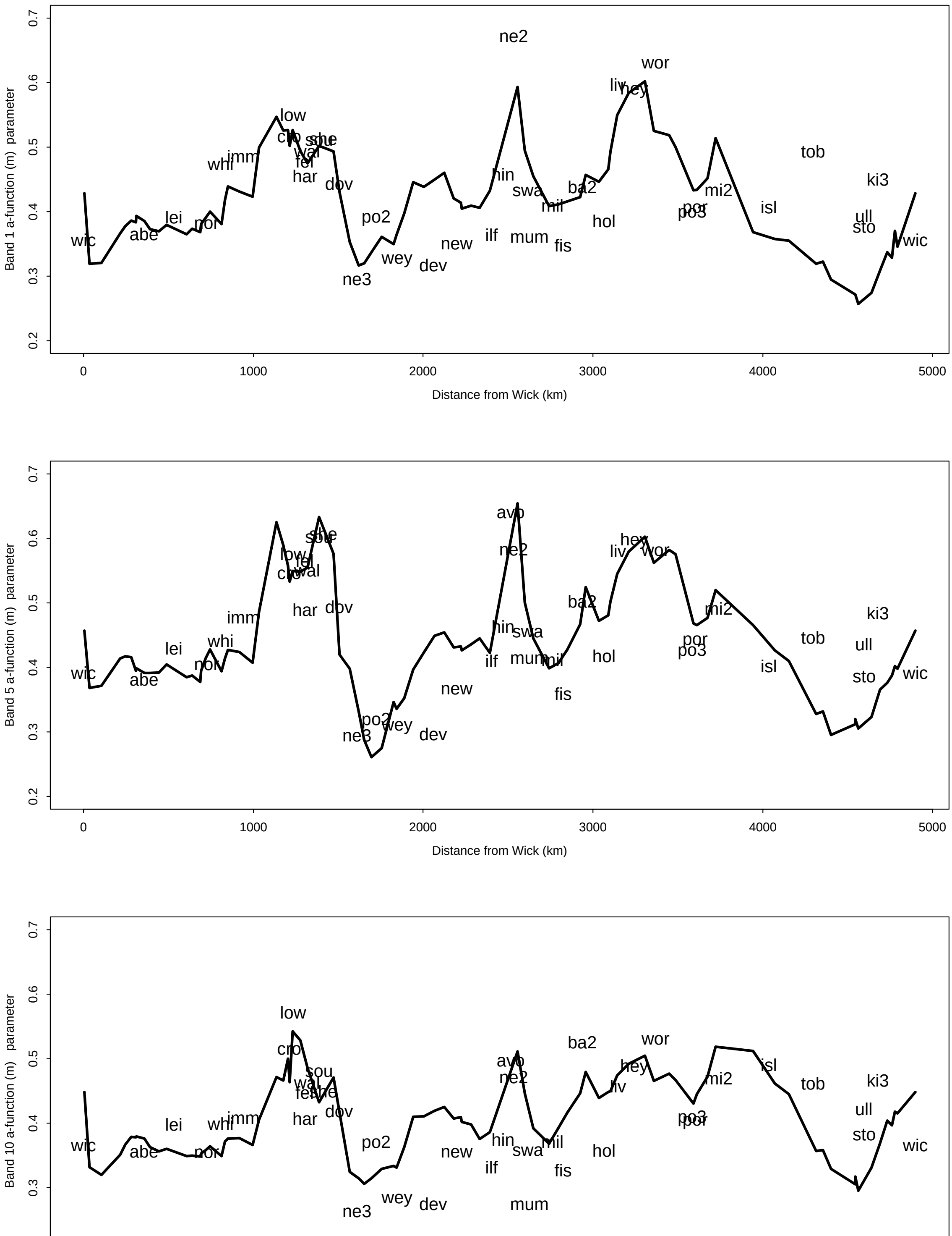

Figure 7.5: Spatial estimate of the unscaled interaction a-function obtained by **Approach IV**: for band 1-low tides, band 5-mid tides, and band 10-high tides. Site estimates are indicated by site abbreviations.

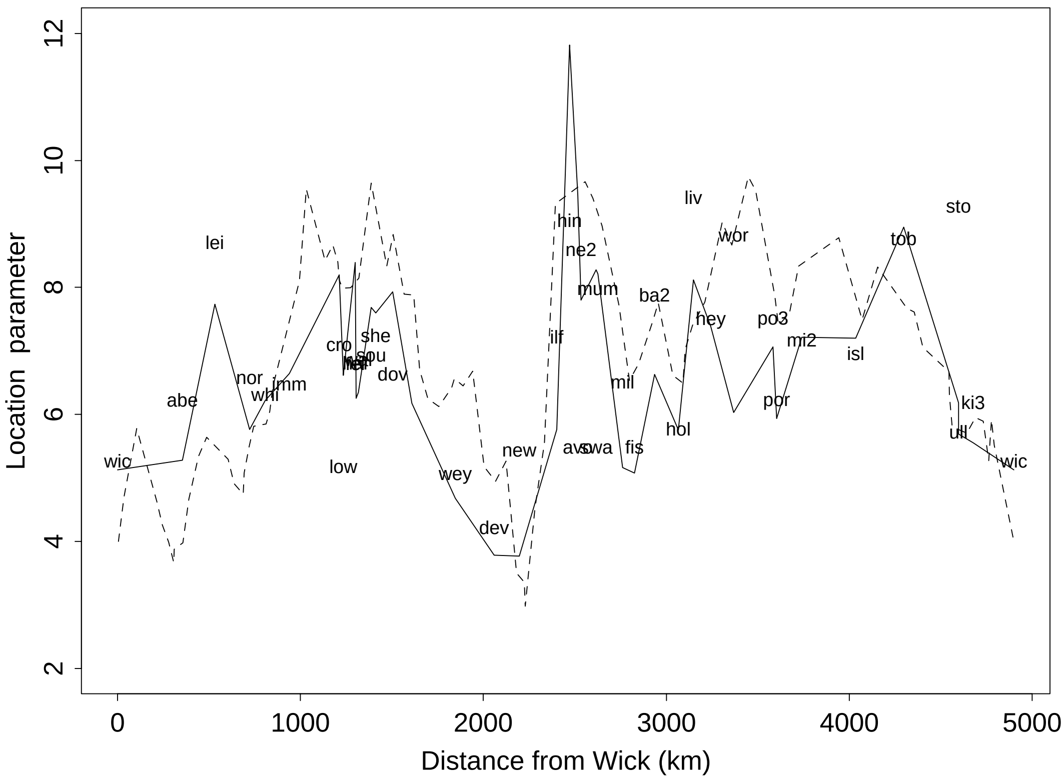

Figure 7.6: Spatial estimate of the location parameter. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site.

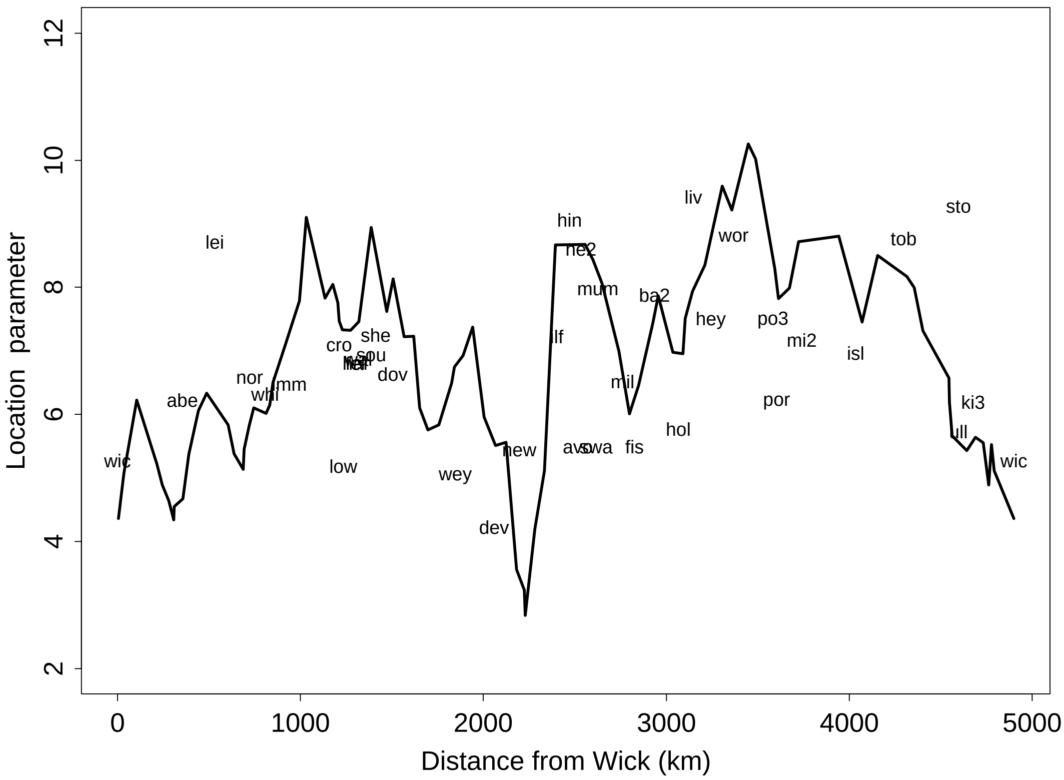

Figure 7.7: Spatial estimate of the location parameter obtained by **Approach IV**. Site estimates are indicated by site abbreviations.

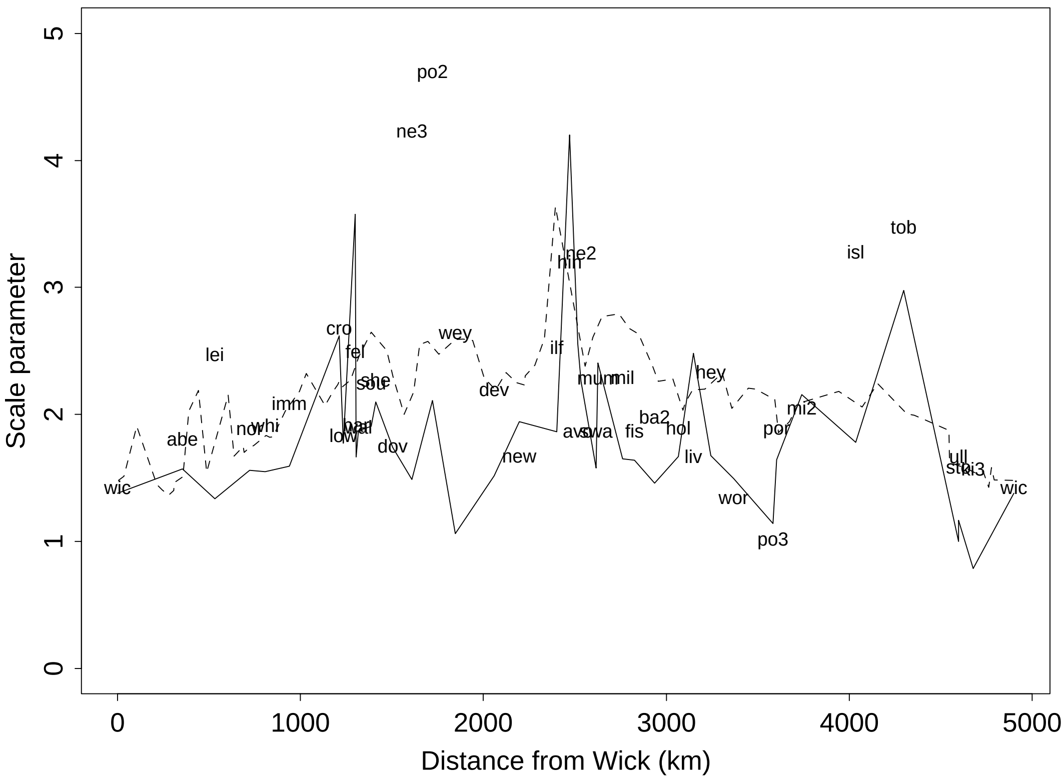

Figure 7.8: Spatial estimate of the scale parameter. The solid line is the estimate obtained from the (unadjusted) overlapping data at the grid point. The broken line is the (unadjusted) full grid data estimate, and the site names are the estimates at the site.

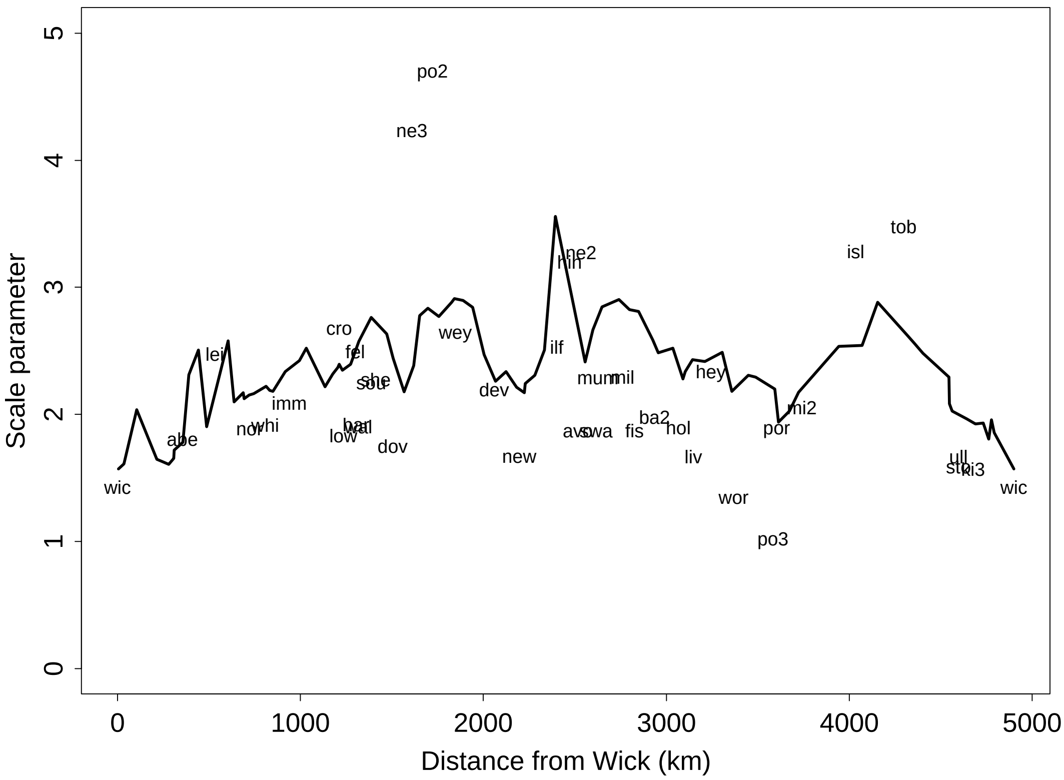

Figure 7.9: Spatial estimate of the scale parameter obtained by **Approach IV**. Site estimates are indicated by site abbreviations.

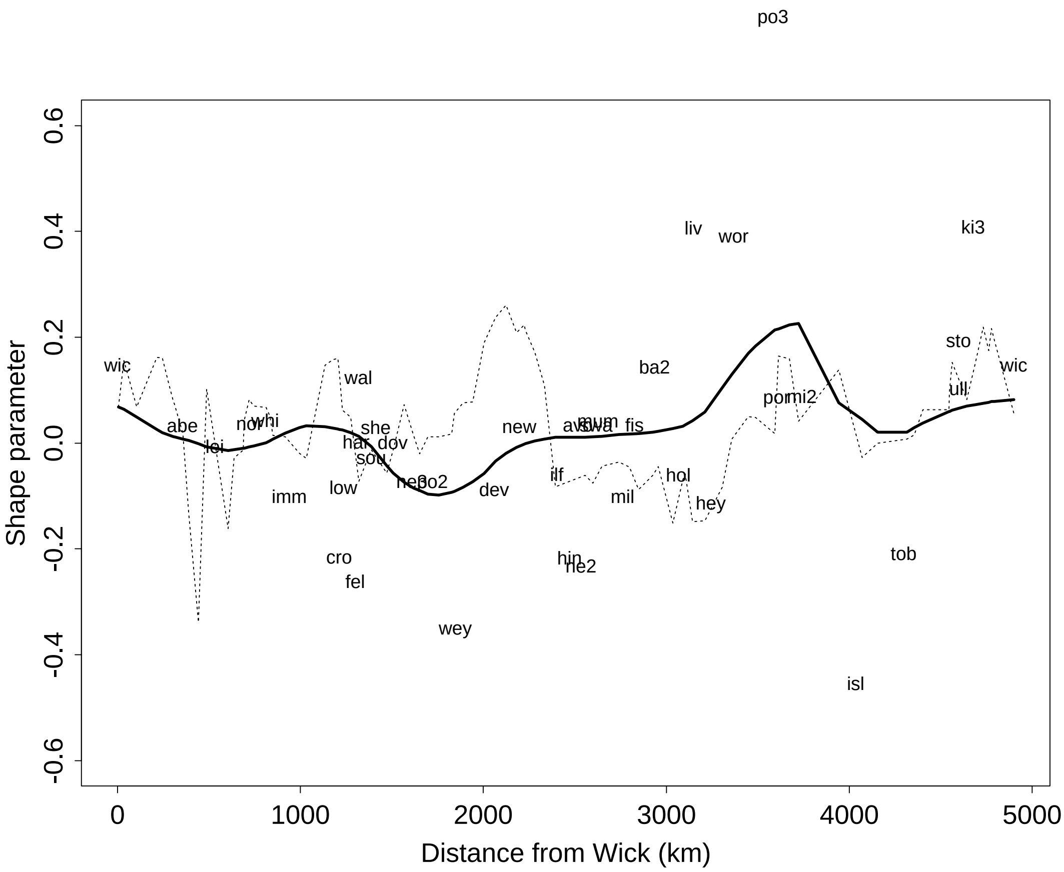

Figure 7.10: Spatial estimate of the shape parameter obtained by **Approach IV**. Site estimates are indicated by site abbreviations.

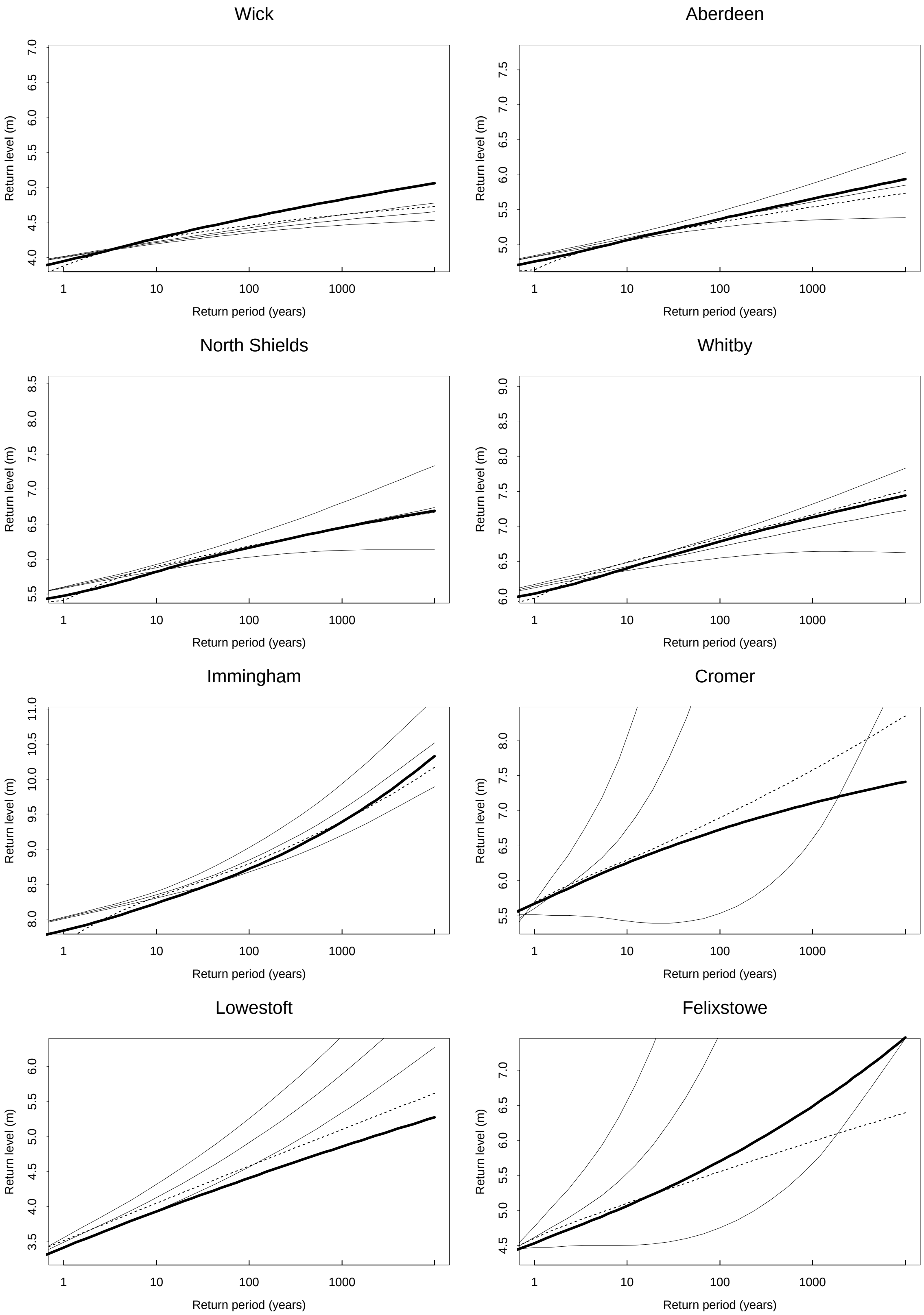

Figure 7.11: Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

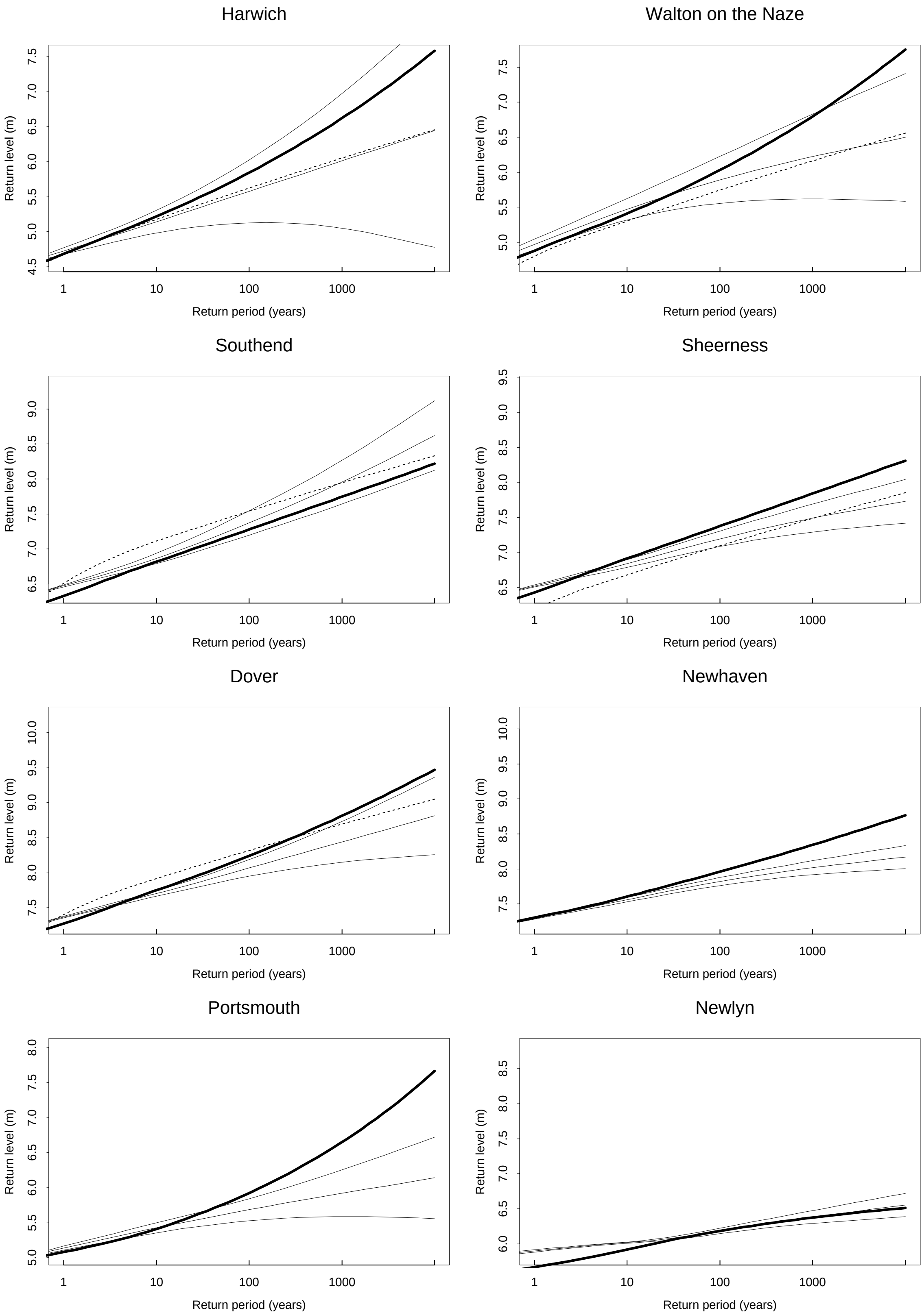

Figure 7.12: Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

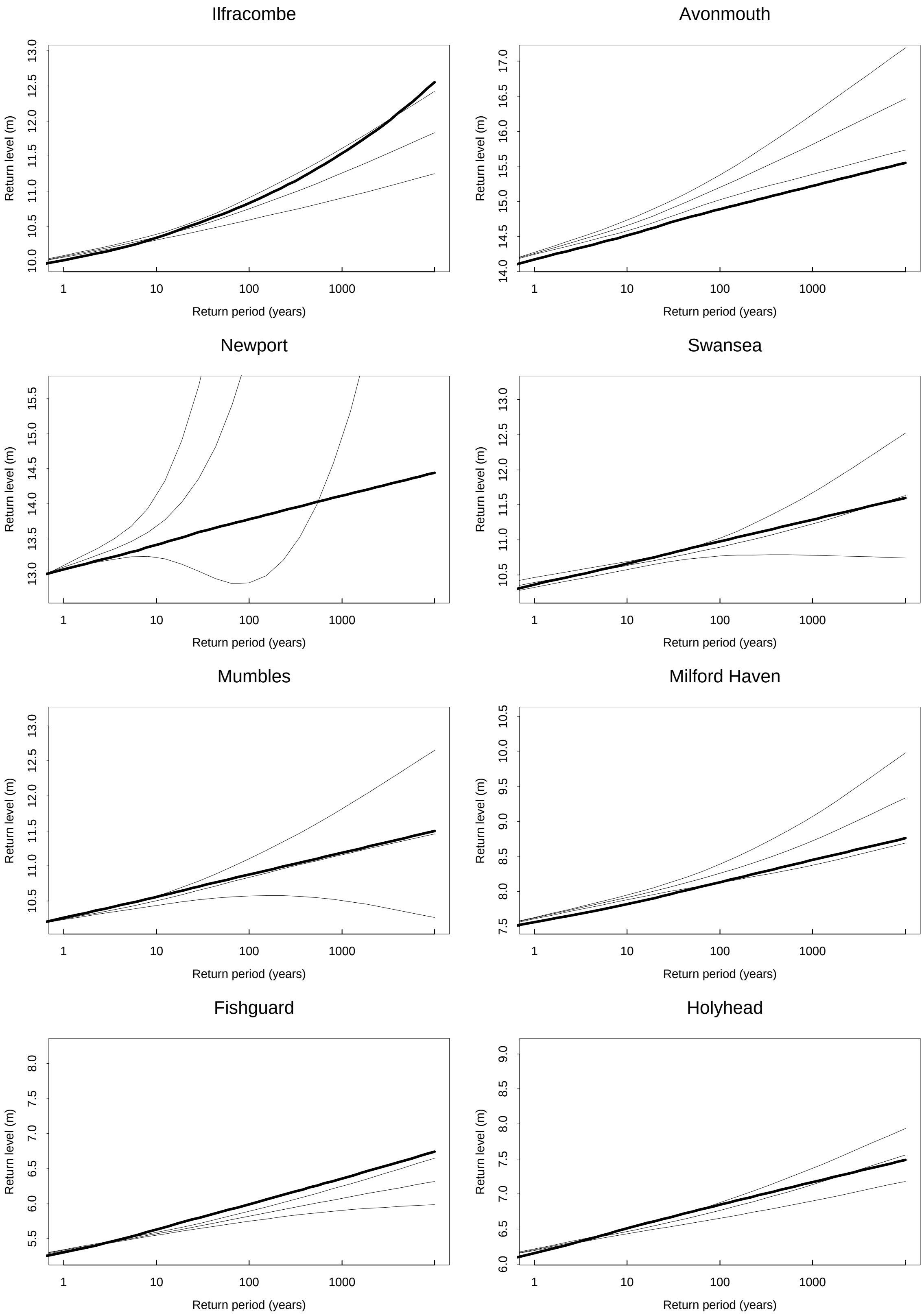

Figure 7.13: Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

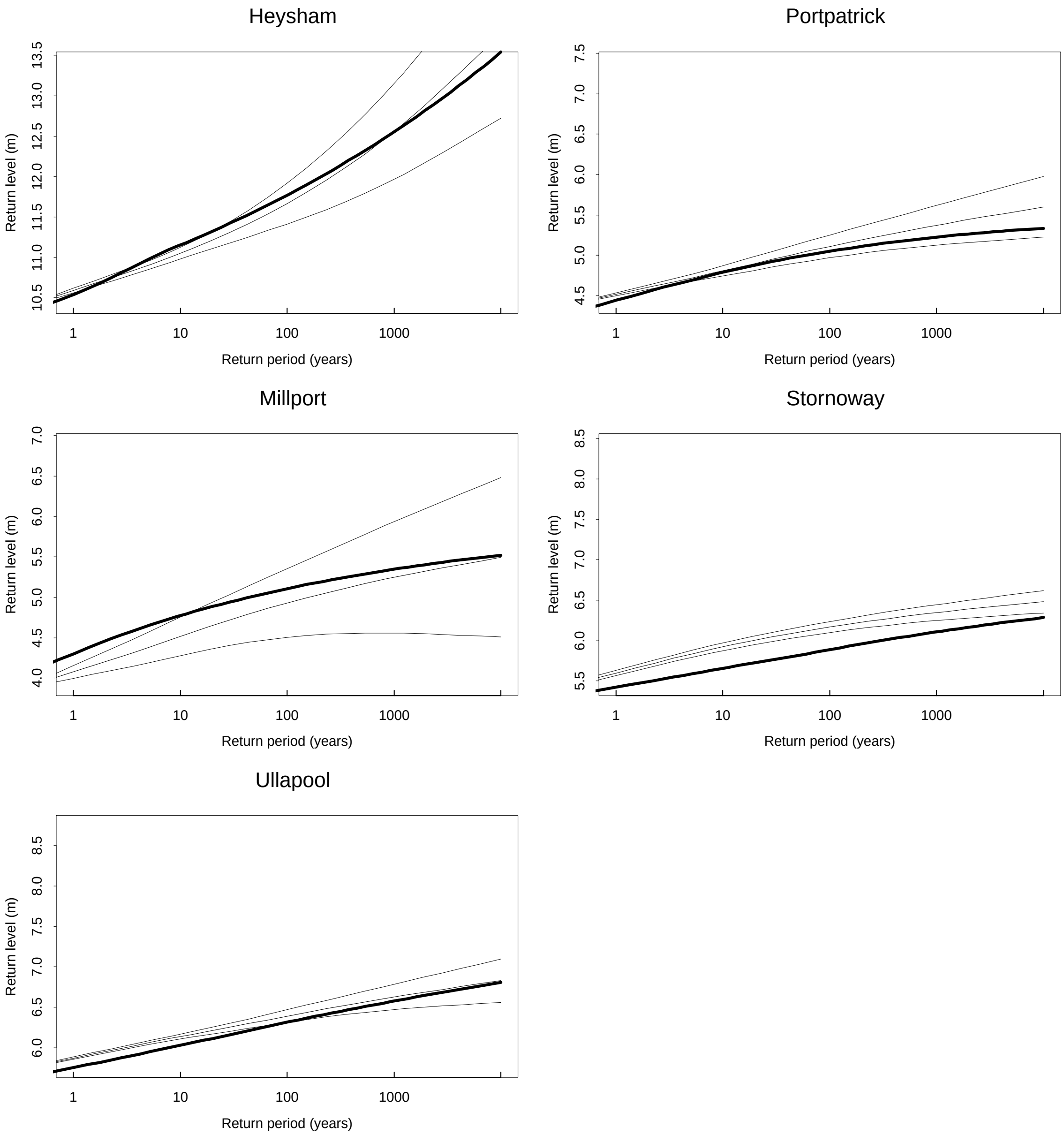

Figure 7.14: Port diagrams at the sites for **Approach IV**. The bold lines are for **Approach IV**. Site values are faint continuous lines, with 95% confidence intervals, and the east coast estimate is shown as a broken line where available.

Site	10 yr	100 yr	1000 yr	10000 yr
Wick	4.27	4.56	4.83	5.06
Aberdeen	5.06	5.35	5.65	5.94
North Shields	5.81	6.15	6.44	6.69
Whitby	6.39	6.76	7.12	7.44
Immingham	8.22	8.68	9.37	10.33
Cromer	6.24	6.71	7.10	7.42
Lowestoft	3.92	4.38	4.85	5.28
Felixstowe	5.05	5.66	6.46	7.47
Harwich	5.20	5.80	6.60	7.58
Walton on the Naze	5.39	5.99	6.78	7.75
Southend	6.80	7.25	7.73	8.22
Sheerness	6.90	7.35	7.83	8.31
Dover	7.74	8.21	8.80	9.47
Newhaven	7.59	7.94	8.33	8.76
Portsmouth	5.40	5.89	6.63	7.67
Newlyn	5.91	6.17	6.37	6.51
Ilfracombe	10.32	10.79	11.51	12.55
Avonmouth	14.51	14.87	15.21	15.55
Newport	13.40	13.76	14.11	14.44
Swansea	10.65	10.96	11.28	11.60
Mumbles	10.55	10.86	11.18	11.50
Milford Haven	7.81	8.11	8.44	8.76
Fishguard	5.62	5.97	6.35	6.74
Holyhead	6.50	6.83	7.16	7.48
Heysham	11.14	11.73	12.53	13.54
Portpatrick	4.78	5.04	5.22	5.33
Millport	4.76	5.09	5.34	5.52
Stornoway	5.65	5.87	6.10	6.28
Ullapool	6.02	6.30	6.57	6.81

Table 7.1: Return level estimates at the data sites, obtained using the site tides in **Approach IV**. Estimates are to ACD.

7.4 Comparisons of results

We now compare the results from the four methods. The following discussion concerns Figures 6.1-6.2 (p 76-77), Figures 6.10-6.11 (p 91-92), Figures 6.15-6.16 (p 98-99) and Figures 7.11-7.14 (p 115-118).

Of the four approaches **Approach I** appears to be the worst whereas, at least superficially, the other three approaches give broadly similar estimates.

Approach I:
This is a crude method and relies completely on the numerical model to capture the characteristics of extreme surges without any calibration. The model used is probably too coarse to expect it to do well but it provides a good starting point for statistical calibration.

Approach II:
If the numerical model contained systematic linear errors in extreme surge predictions then this approach would work well. The method allows for the additive errors to change smoothly around the coast. However, when fitting this model it was clear that errors were far from additive, often taking quite different forms for extreme surges than typical surges, and in places varying very quickly along the coast. Thus although the estimates from this approach are slightly better than those from **Approach I** they cannot, in general, be trusted.

Approach III:
This method relies on bias-correcting the return level estimates empirically and using these bias terms to improve on the **Approach I** estimates. The method is crude in its statistical basis, and is given primarily as a baseline to be improved upon. This is the approach which would be taken when only return level estimates for the grid-points and the data sites but not the data are available. Nevertheless, the method does improve on **Approach I** at least at the data sites.

Approach IV:
This is our favoured method based on both statistical validity and the results obtained. The method recognises that there are a number of different features of extreme sea-levels: tides, interaction between tide and surge, and extreme surges. These change along a coastline smoothly, but can vary, leading to complex changing return levels (hence **Approach III** can be poor at interpolating). These physical characteristics can be estimated separately from the site data and the numerical model data. The numerical model may give a consistent bias to one of these features along a coastline. Often this bias may not be removed by simple linear scaling of the data as attempted by **Approach II**. However by modifying the coastal estimate of this parameter from the numerical model data we are able to improve agreement with site data and provide a basis for each of the key characteristics of the extreme sea-level process.

file 4

Chapter 8

Results: tables and figures

In this chapter we give return level estimates for the 89 coastal positions around the UK. The tabulated results are, in general, at a sufficiently high spatial resolution to enable the calculation of return levels for any latitude-longitude position on the coastline. The spatial tide estimates are used in obtaining return levels, so that the results differ from those obtained in Chapter 7 at nearest-site grid points.

Conditional on the validity of the assumption that the numerical model data represent the site data, the results in this chapter provide the most up-to-date estimates, and supersede those given previously in DT1 and DT2. The quality of the return level estimates obtained from applying **Approach IV** with the spatially derived tides depends on the quality of

- the spatial mapping of tides
- the spatial modelling of extreme surges.

It turns out to be convenient to quote results for the spatial model by separating the sea-level process into two components. A spatial estimate is obtained for each component, and these are then recombined to give estimates of return levels at every coastal point. In particular, extreme sea-levels are split into two components,

1. extreme sea-levels which are very rare, and which have not usually been observed over the period of available data, and
2. extreme sea-levels which are relatively common, and have been observed frequently over the data-span.

There are a number of statistics that could be used to summarise these two components. We choose to use the following.

1. The T year return level relative to the 1 year return level.

2. The 1 year return level.

Estimation of these components requires two fundamentally different approaches. We have concentrated in Chapters 5-7 on how to model the first component. The second component, the 1 year return level, can be estimated accurately by applying some form of the joint probability method (Pugh and Vassie, 1980) to a year or more of hourly sea-level data at a site. Although the estimates at each site are generally very precise, this component can vary substantially from point to point along the coastline, especially around complex shaped parts of the coastline, for example in estuaries and inlets. Thus for component 2, care is required when interpolating estimates *between* sites.

The overall return level estimate is given by adding these two estimates together and adjusting, in Section 8.4,

1. to the datum of interest
2. for trends.

In Section 8.3 we show how to obtain the distance (using our metric) of any coastal location given its latitude-longitude. Table 4.1 (p57) gives the latitudes, longitudes, and the corresponding distance defined by the distance metric in Chapter 5, for each of the 89 grid points. Tables 4.2 and 4.3 (p58 and p59) gives the distances, and positions for the A class sites. In Section 8.5, we present some examples showing how to calculate a return level estimate at a particular location, and finally in Section 8.6 we compare our spatial results with those obtained from annual maximum data in Coles and Tawn (1990).

Unless otherwise stated, all results are given relative to MSL. We have not calculated standard errors for the spatial estimate as the main source of uncertainty is in the spatial tidal estimate between data sites. This uncertainty is difficult to quantify as it arises from the numerical model limitations on the 12km grid which depend critically (and unpredictably) on the local bathymetry and on the geometry of the nearby coastline, with complex shaped regions having greater uncertainty than simple linear coastal stretches. An approximate guide to the standard errors is given by the nearest long record site in Tables 10 and 11 of DT1.

8.1 Relative return level results

The first stage is to obtain the estimated difference

$$D_T(d) = z_T(d) - z_1(d) \tag{8.1.1}$$

between the estimated T and 1 year return levels for all values, d, of the distance metric. Figures 8.1–8.4 show this spatial estimate, for all d, for $T = 10, 100, 1000$ and 10000. This spatial estimate is given in more detail in Figures 8.5–8.8 which show the spatial estimate on a better scale, and is tabulated in Tables 8.1–8.3.

On Figures 8.1–8.4 we have also shown various other estimates of this return level difference. Explicitly, for comparison we have shown estimates based on **Approach I** and for the data sites, the site-by-site estimates derived in DT1 and DT2. The symbols used for the site estimates correspond to

$\circ$	r-largest method (Rlarg)
$\triangle$	joint probability method (JPM)
$+$	revised joint probability method (RJPM)
$\times$	spatial revised joint probability method (SRJPM)
$\diamond$	East coast spatial model (Ecst)
∇	Approach IV (App IV)

The key feature to observe from all the estimates shown in Figures 8.1–8.4 is the small, and smooth, spatial variation in levels around the entire coastline. For each of the return level differences presented the pattern of spatial variation is similar:

- a gradual increase in the difference is obtained moving south along the east coast,
- the difference is stable over the Lowestoft–Dover stretch,
- a decrease in the difference along the south coast when passing from east to west,
- a gradual increase from Newlyn to Ilfracombe, followed by a stable value in the Bristol Channel to near Swansea,
- constant difference from Swansea to Fishguard,
- a gradual increase from Fishguard to Holyhead followed by a sharp increase to Liverpool and the Morecambe Bay region,

- from Workington right around to Wick there is a steady decrease, with a slight increase in the Millport region.

Now consider the performance of **Approach IV** relative to the other estimates. For much of the coastline, **Approach IV** and **Approach I** do not differ greatly. However at some places the **Approach I** estimate is poor. For example, at distances of around 400-600km, the 100 year return level (and above) is significantly overestimated. Elsewhere, where the estimates from **Approaches I** and **IV** differ, the latter is generally the better as measured by the comparison with site estimates (e.g. the south east coast and the Bristol Channel), but possibly worse in Morecambe Bay.

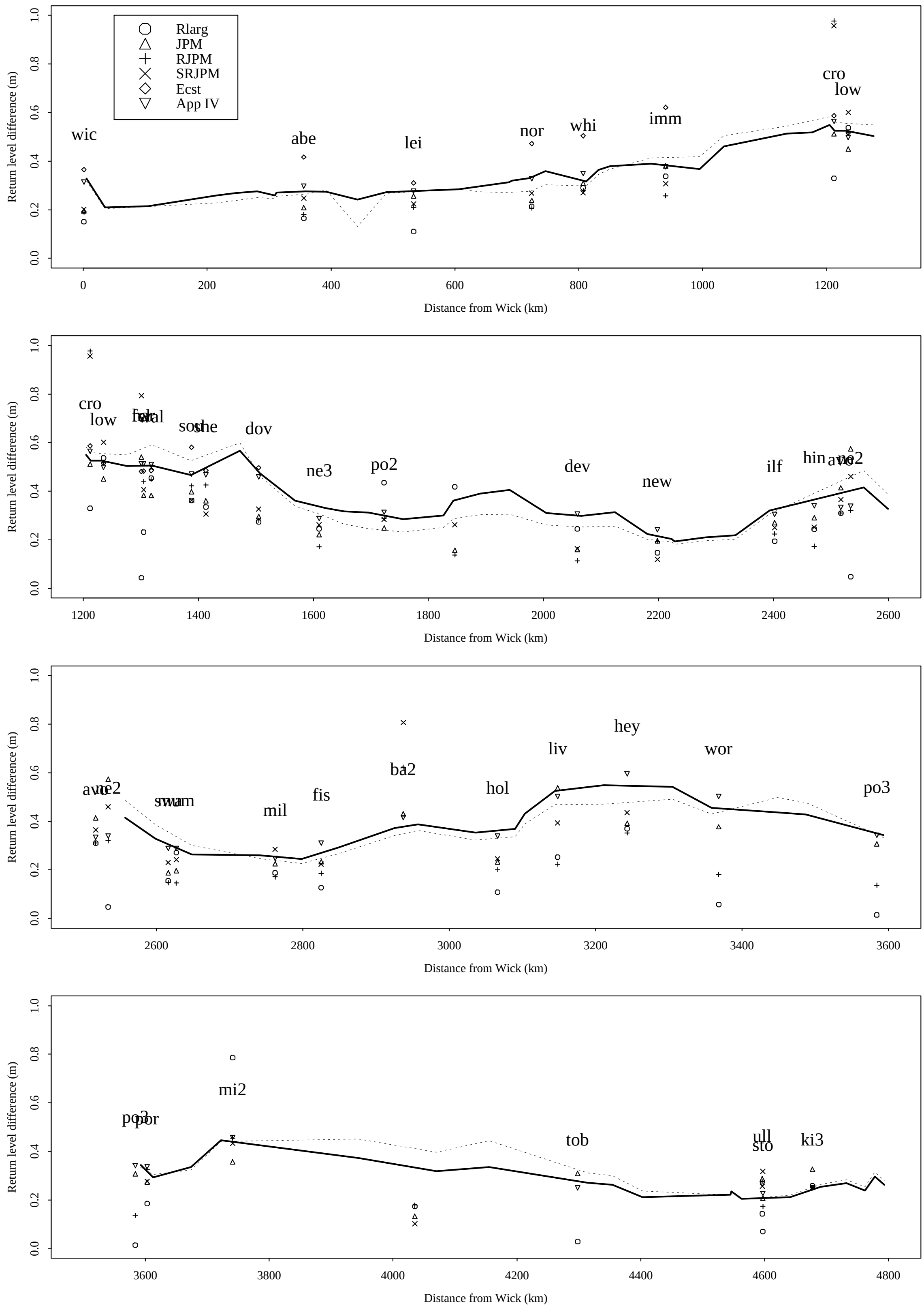

Figure 8.1: Spatial estimate of the 10 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown.

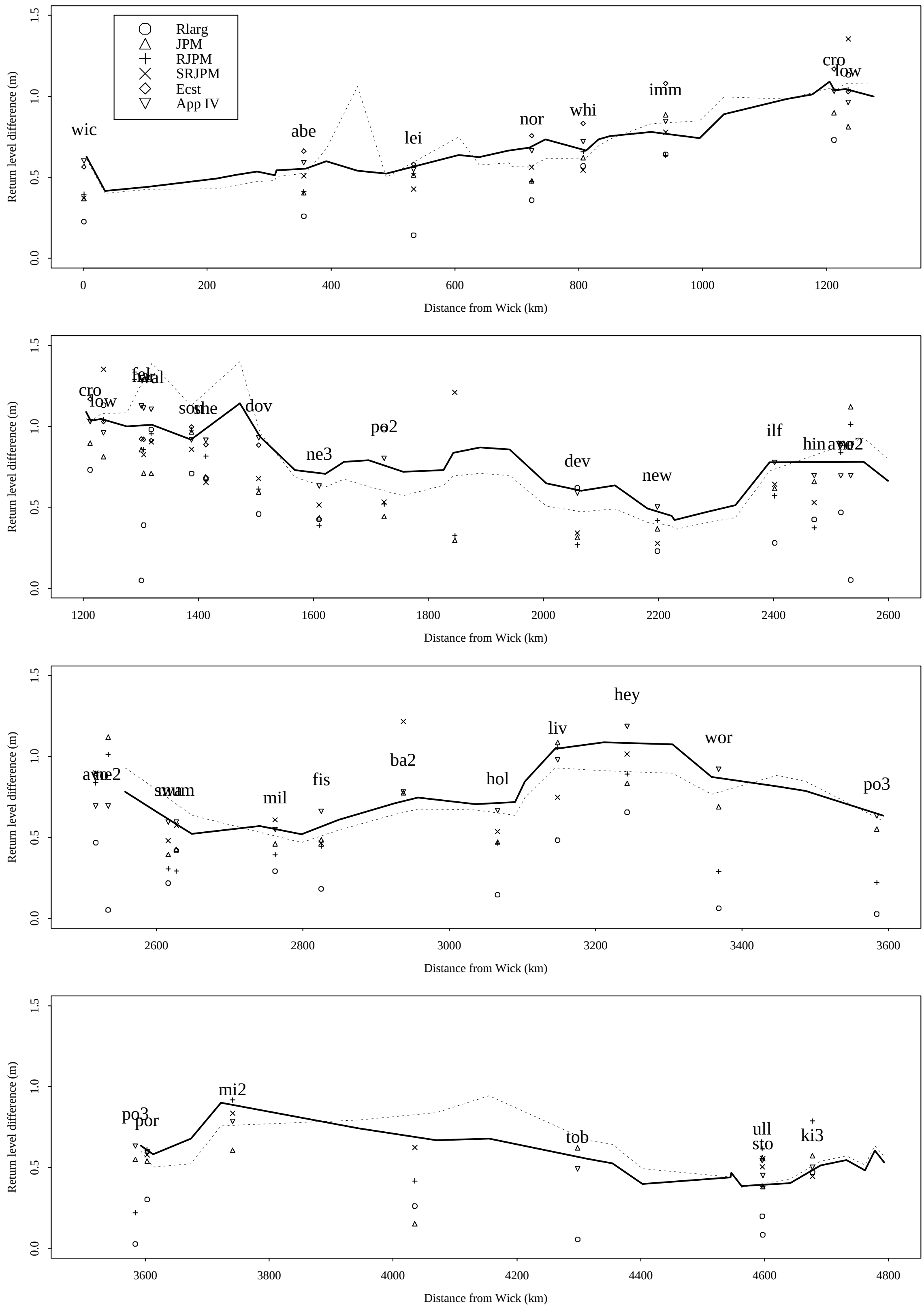

Figure 8.2: Spatial estimate of the 100 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown.

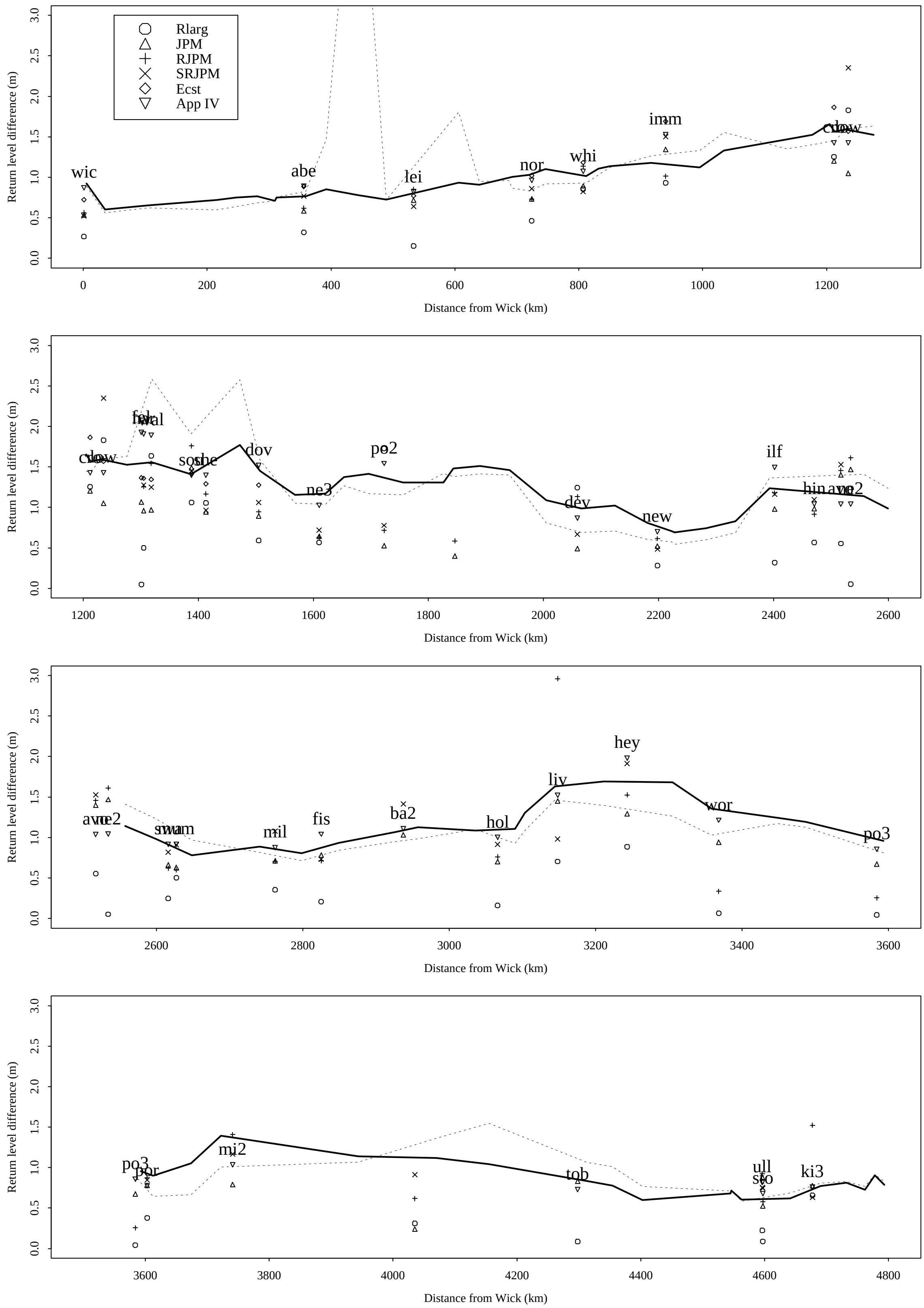

Figure 8.3: Spatial estimate of the 1000 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown.

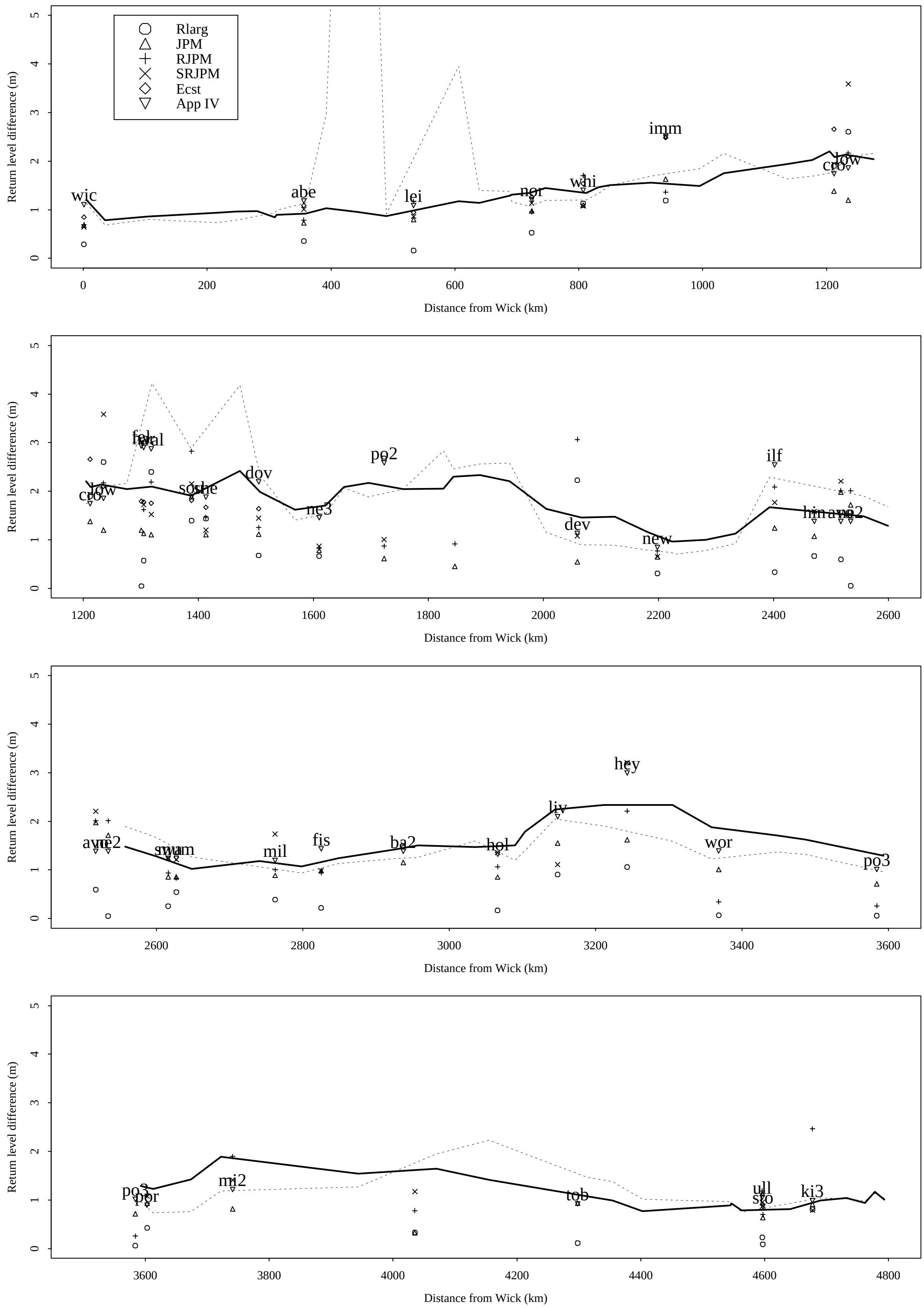

Figure 8.4: Spatial estimate of the 10000 year return level minus the 1 year level. The heavy solid, and faint broken lines, represent **Approach IV** and **Approach I** respectively. Site estimates, obtained using the site tides, of the difference are shown.

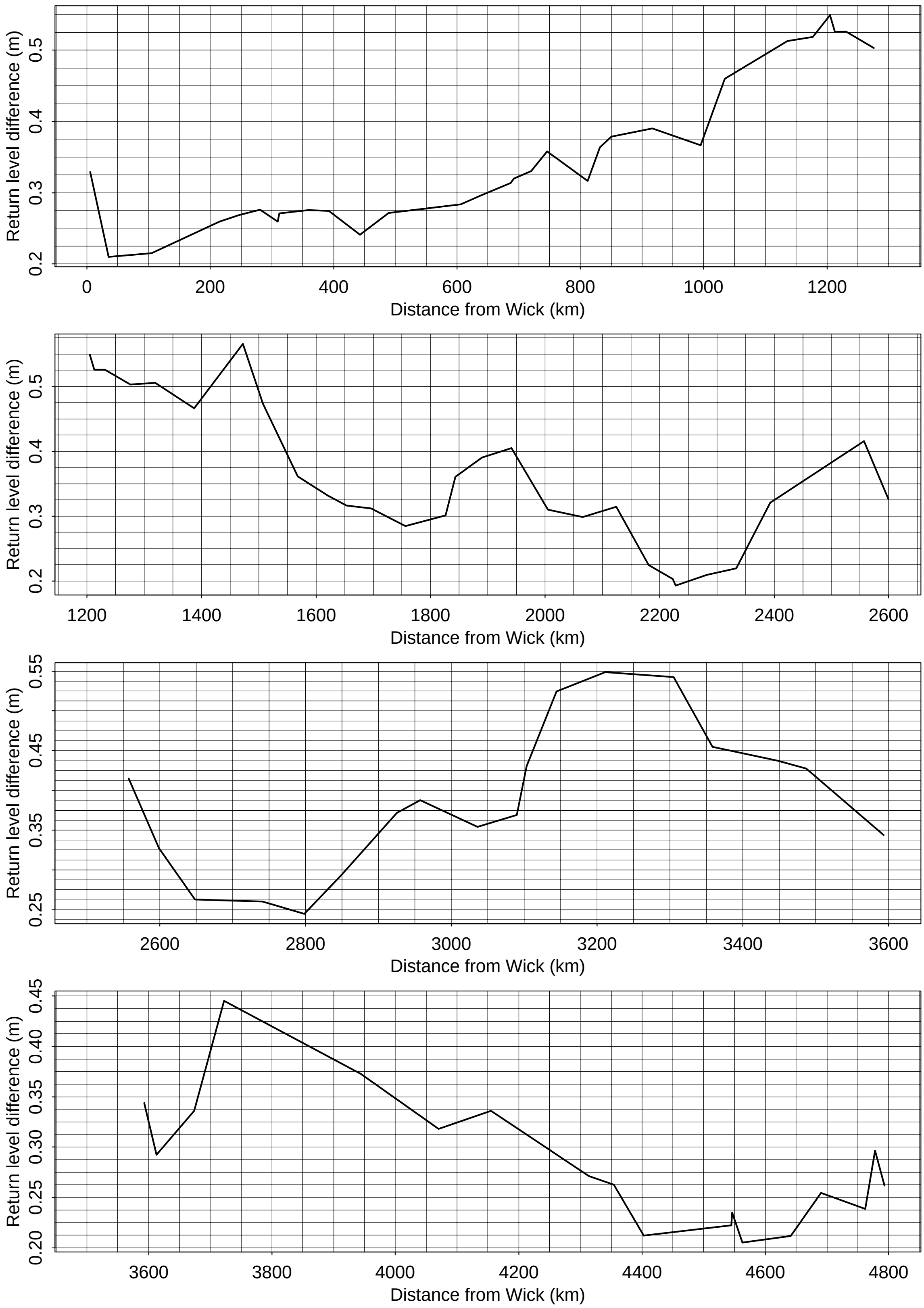

Figure 8.5: Spatial estimate of the difference between the 10 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides.

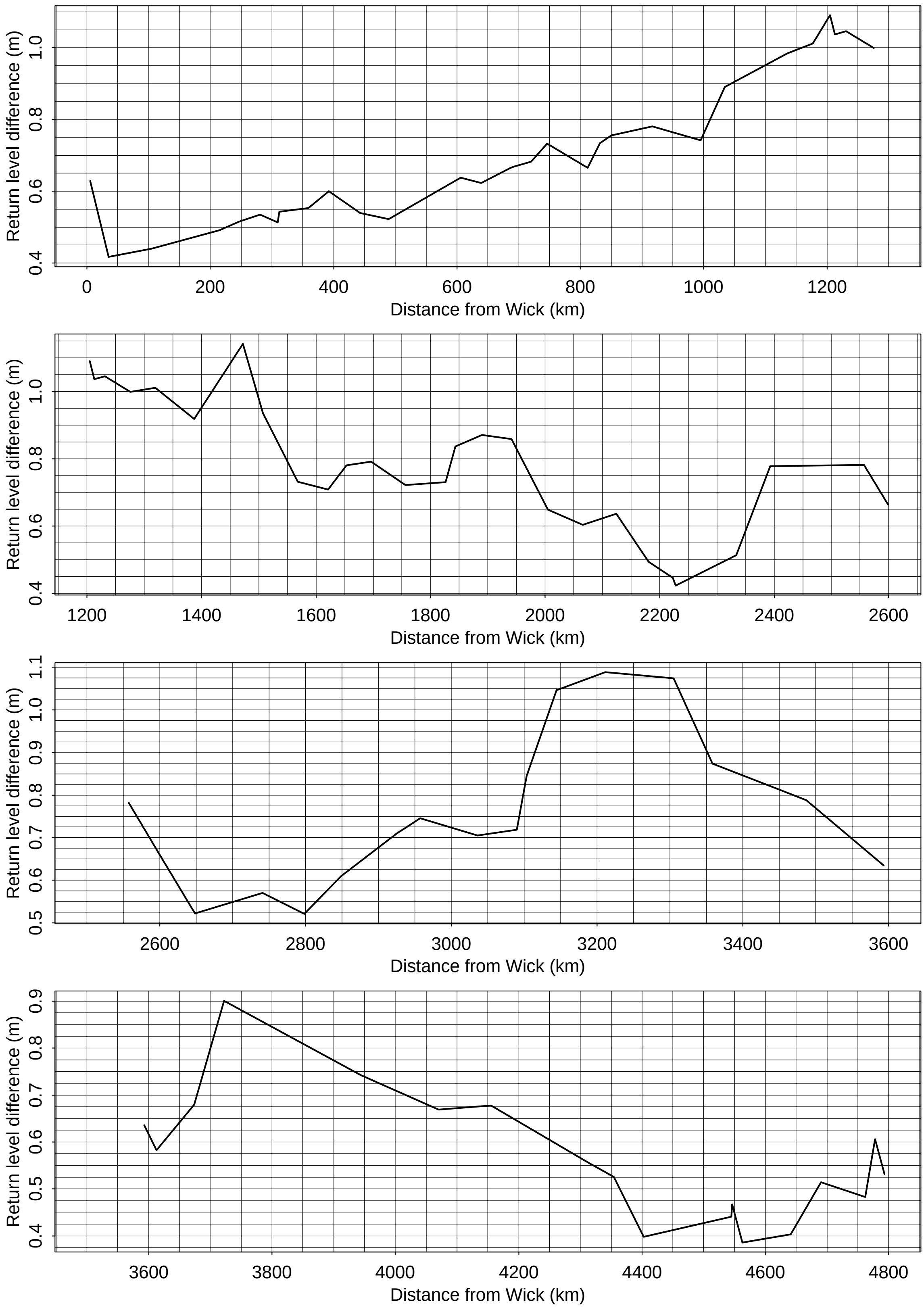

Figure 8.6: Spatial estimate of the difference between the 100 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides.

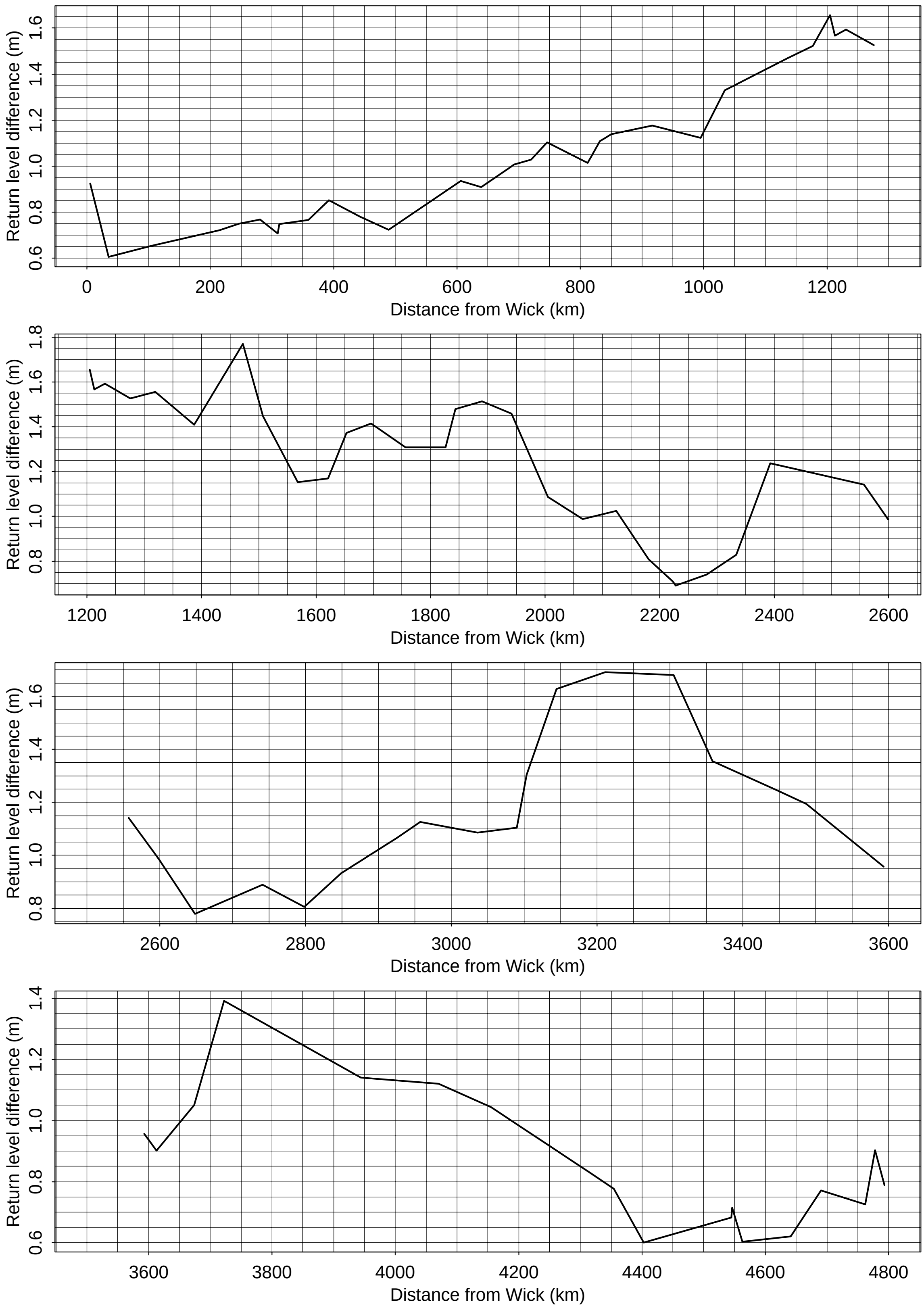

Figure 8.7: Spatial estimate of the difference between the 1000 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides.

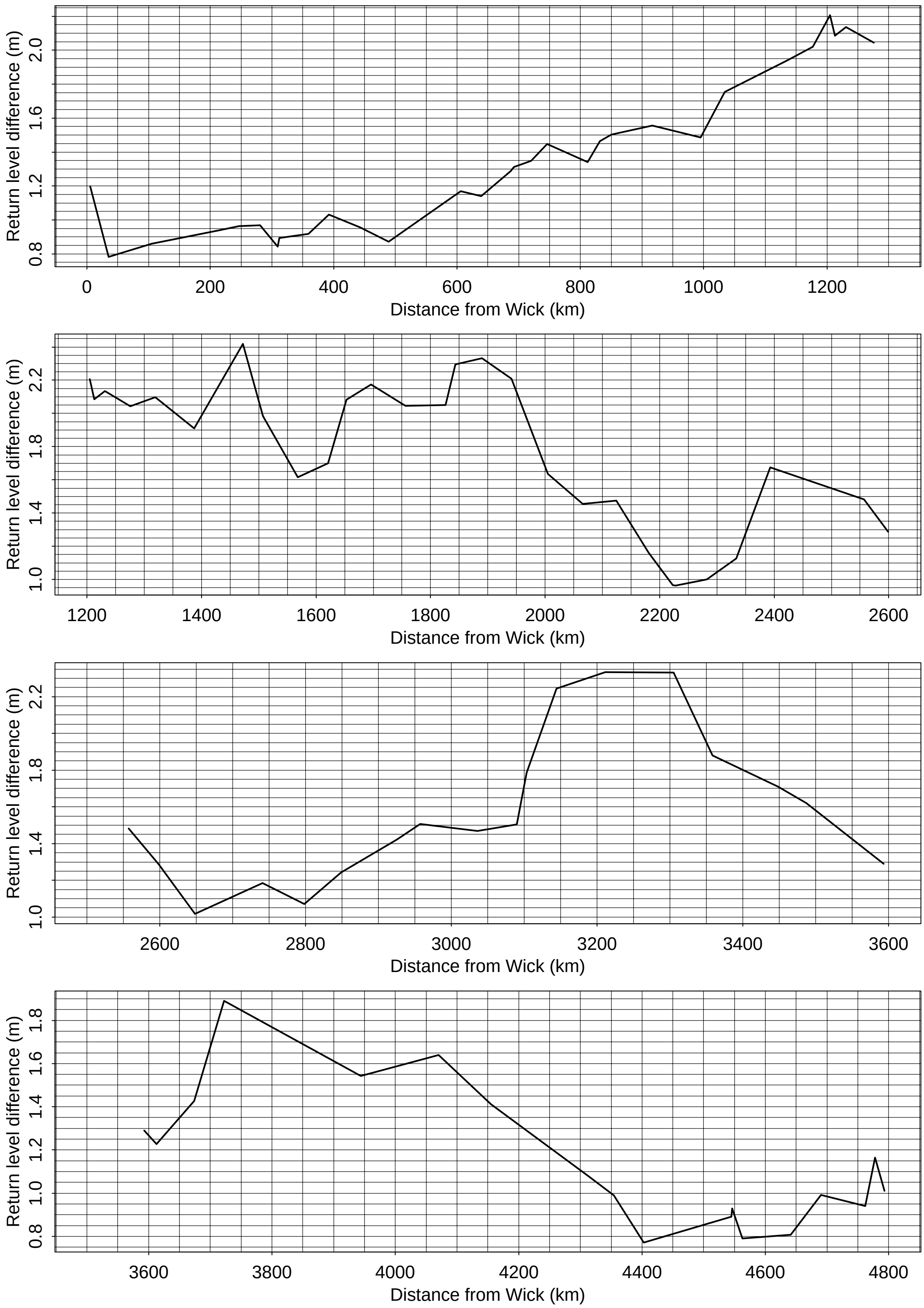

Figure 8.8: Spatial estimate of the difference between the 10000 year return level and the 1 year level as estimated using **Approach IV** using the spatially mapped tides.

Distance	10	25	50	100	250	500	1000	10000
-5	0.23	0.33	0.38	0.46	0.54	0.58	0.64	0.81
5	0.33	0.46	0.53	0.65	0.77	0.83	0.92	1.20
35	0.21	0.30	0.36	0.43	0.51	0.55	0.61	0.78
105	0.21	0.32	0.37	0.46	0.54	0.59	0.65	0.86
215	0.26	0.36	0.42	0.51	0.60	0.65	0.72	0.94
247	0.27	0.38	0.44	0.53	0.63	0.68	0.75	0.96
281	0.28	0.39	0.45	0.55	0.65	0.70	0.77	0.97
309	0.26	0.38	0.44	0.53	0.61	0.66	0.71	0.84
312	0.27	0.40	0.46	0.56	0.65	0.69	0.75	0.89
359	0.28	0.40	0.47	0.57	0.66	0.71	0.77	0.92
392	0.27	0.42	0.50	0.62	0.73	0.78	0.85	1.03
443	0.24	0.37	0.45	0.56	0.66	0.71	0.78	0.96
489	0.27	0.39	0.45	0.54	0.62	0.67	0.72	0.87
606	0.28	0.44	0.53	0.66	0.78	0.85	0.94	1.17
639	0.30	0.44	0.52	0.65	0.76	0.83	0.91	1.14
687	0.31	0.47	0.55	0.69	0.82	0.90	1.00	1.29
692	0.32	0.47	0.56	0.70	0.83	0.90	1.01	1.31
720	0.33	0.48	0.57	0.71	0.85	0.92	1.03	1.35
746	0.36	0.52	0.61	0.76	0.91	0.99	1.10	1.45
812	0.32	0.47	0.55	0.69	0.83	0.91	1.01	1.34
832	0.36	0.52	0.61	0.76	0.91	1.00	1.11	1.46
850	0.38	0.54	0.63	0.79	0.93	1.02	1.14	1.50
917	0.39	0.56	0.65	0.81	0.97	1.06	1.18	1.56
995	0.37	0.53	0.62	0.77	0.92	1.01	1.12	1.49
1034	0.46	0.65	0.75	0.92	1.10	1.20	1.33	1.75
1136	0.51	0.71	0.83	1.02	1.21	1.32	1.47	1.94
1177	0.52	0.73	0.85	1.05	1.25	1.37	1.52	2.02
1205	0.55	0.78	0.91	1.14	1.35	1.48	1.66	2.21
1213	0.53	0.74	0.87	1.08	1.28	1.41	1.57	2.08
1231	0.53	0.74	0.87	1.09	1.30	1.43	1.59	2.14

Table 8.1: Return level estimates (in metres), for return periods 10, 25, 50, 100, 250, 500, 1000, and 10000 years, relative to the 1 year level for the east coast.

Distance	10	25	50	100	250	500	1000	10000
1276	0.50	0.71	0.84	1.04	1.24	1.36	1.53	2.04
1319	0.51	0.72	0.85	1.05	1.26	1.39	1.56	2.10
1387	0.47	0.66	0.77	0.95	1.14	1.26	1.41	1.91
1472	0.57	0.81	0.95	1.19	1.43	1.58	1.77	2.42
1507	0.47	0.67	0.78	0.97	1.17	1.29	1.45	1.98
1568	0.36	0.52	0.61	0.76	0.92	1.02	1.15	1.62
1621	0.33	0.48	0.58	0.74	0.91	1.02	1.17	1.70
1653	0.32	0.50	0.62	0.82	1.04	1.18	1.37	2.08
1696	0.31	0.50	0.62	0.84	1.06	1.21	1.41	2.17
1756	0.28	0.46	0.57	0.76	0.98	1.11	1.31	2.05
1826	0.30	0.47	0.58	0.77	0.98	1.12	1.31	2.05
1843	0.36	0.55	0.67	0.88	1.11	1.26	1.48	2.30
1890	0.39	0.58	0.70	0.91	1.15	1.30	1.51	2.33
1941	0.40	0.58	0.70	0.90	1.12	1.26	1.46	2.21
2005	0.31	0.45	0.53	0.68	0.84	0.94	1.09	1.63
2066	0.30	0.43	0.50	0.63	0.77	0.86	0.99	1.45
2124	0.31	0.45	0.53	0.66	0.81	0.90	1.02	1.47
2181	0.22	0.34	0.40	0.52	0.63	0.71	0.81	1.16
2223	0.20	0.30	0.36	0.47	0.57	0.63	0.71	0.96
2228	0.19	0.28	0.34	0.44	0.55	0.61	0.69	0.96
2282	0.21	0.32	0.38	0.49	0.60	0.66	0.74	1.00
2334	0.22	0.34	0.41	0.54	0.66	0.73	0.83	1.13
2393	0.32	0.52	0.63	0.81	0.99	1.10	1.24	1.67
2557	0.42	0.57	0.66	0.81	0.95	1.03	1.14	1.48
2599	0.33	0.48	0.56	0.69	0.81	0.89	0.99	1.29
2648	0.26	0.38	0.44	0.54	0.64	0.70	0.78	1.02
2741	0.26	0.39	0.47	0.60	0.72	0.79	0.89	1.19
2798	0.24	0.36	0.43	0.54	0.65	0.72	0.81	1.07
2849	0.29	0.43	0.51	0.63	0.76	0.83	0.93	1.24
2925	0.37	0.51	0.60	0.74	0.87	0.96	1.07	1.42

Table 8.2: Return level estimates, in metres, for return periods 10, 25, 50, 100, 250, 500, 1000, and 10000 years, relative to the 1 year level for the south coast.

Distance	10	25	50	100	250	500	1000	10000
2925	0.37	0.51	0.60	0.74	0.87	0.96	1.07	1.42
2957	0.39	0.54	0.63	0.77	0.92	1.01	1.13	1.51
3036	0.35	0.50	0.59	0.74	0.88	0.97	1.09	1.47
3090	0.37	0.52	0.60	0.75	0.90	0.98	1.10	1.50
3103	0.43	0.60	0.71	0.88	1.05	1.16	1.30	1.79
3144	0.52	0.74	0.87	1.09	1.31	1.45	1.63	2.24
3211	0.55	0.77	0.91	1.13	1.36	1.50	1.69	2.33
3305	0.54	0.76	0.90	1.12	1.35	1.49	1.68	2.33
3358	0.45	0.63	0.73	0.91	1.09	1.20	1.36	1.88
3448	0.44	0.59	0.69	0.85	1.01	1.11	1.24	1.71
3487	0.43	0.58	0.67	0.82	0.97	1.07	1.19	1.62
3593	0.34	0.47	0.54	0.66	0.78	0.86	0.96	1.29
3613	0.29	0.41	0.49	0.61	0.73	0.80	0.90	1.23
3674	0.34	0.48	0.57	0.71	0.85	0.94	1.05	1.43
3722	0.45	0.64	0.75	0.94	1.13	1.24	1.39	1.89
3944	0.37	0.53	0.62	0.77	0.93	1.02	1.14	1.54
4070	0.32	0.46	0.55	0.70	0.87	0.97	1.12	1.64
4155	0.34	0.48	0.57	0.71	0.85	0.93	1.04	1.41
4314	0.27	0.39	0.46	0.58	0.69	0.75	0.83	1.08
4354	0.26	0.37	0.44	0.55	0.65	0.70	0.78	0.99
4403	0.21	0.29	0.34	0.42	0.50	0.54	0.60	0.77
4545	0.22	0.31	0.36	0.46	0.56	0.61	0.68	0.89
4546	0.23	0.33	0.39	0.49	0.59	0.64	0.72	0.93
4563	0.21	0.29	0.33	0.40	0.49	0.54	0.60	0.79
4641	0.21	0.30	0.34	0.42	0.51	0.56	0.62	0.81
4690	0.25	0.36	0.43	0.54	0.64	0.70	0.77	0.99
4732	0.27	0.38	0.46	0.57	0.67	0.73	0.81	1.04
4762	0.24	0.34	0.40	0.50	0.60	0.65	0.73	0.94
4778	0.30	0.43	0.51	0.63	0.75	0.82	0.90	1.16
4793	0.26	0.38	0.44	0.55	0.65	0.71	0.79	1.01

Table 8.3: Return level estimates, in metres, for return periods 10, 25, 50, 100, 250, 500, 1000, and 10000 years, relative to the 1 year level for the west coast.

8.2 The one year return level

The basic spatial estimate we have for the 1 year level is obtained by applying **Approach IV** directly at the grid points using the spatially mapped tides. A map of this estimate, around the coast is given in Figure 8.9. There is considerably greater spatial variation in the estimated 1 year level than found in Section 8.1 for the difference between the T and 1 year return level estimates.

Also shown on Figure 8.9 are the site estimates of the 1 year return level obtained by using the joint probability method of Pugh and Vassie (1980). The spatial estimate agrees well with the site values in general. However, given the scale of the plot, even small differences between these estimates corresponds to poor estimates from the spatial approach due to the tides being badly modelled. The spatial estimate is particularly poor in the regions

- Humber-Wash (Distance of 900-1200km)
- Bristol Channel (Distance of 2500km)
- Liverpool-Morecambe Bay, (Distance of 3100-3500km)

which are regions which require more detailed numerical models. Of these regions, only the Bristol Channel is studied in this report (in Chapter 9).

The spatial estimate of the 1 year return level can be improved by calibrating the spatial estimate of the one year return level using the site estimates of the 1 year level. The technique we use for calibration is that applied to parameters in **Approach IV**. The resulting calibrated estimate is shown on Figure 8.9 as a solid line and agrees with the site estimates at the data sites while retaining the structure of the tides between data sites (e.g. between Immingham and Cromer, and between Dover and Newhaven). These values are tabulated in Table 8.4 and for the sites in Table 8.5

Due to the location-specific nature of the tidal series, our recommendation is to obtain an estimate of the 1-year level using data from the location whenever possible. A satisfactory estimate of this level could be obtained from as little 1-6 months of winter period hourly tide and surge data, although we would generally recommend using a year of hourly data to avoid seasonal bias and reduce sampling variation. The Proudman Oceanographic Laboratory are able routinely to provide estimates of the one year return level.

Comparisons of the one year level are made in Section 8.6, where it is shown that for some complex shaped coastal regions, the one year level is poorly estimated by simple interpolation between grid points.

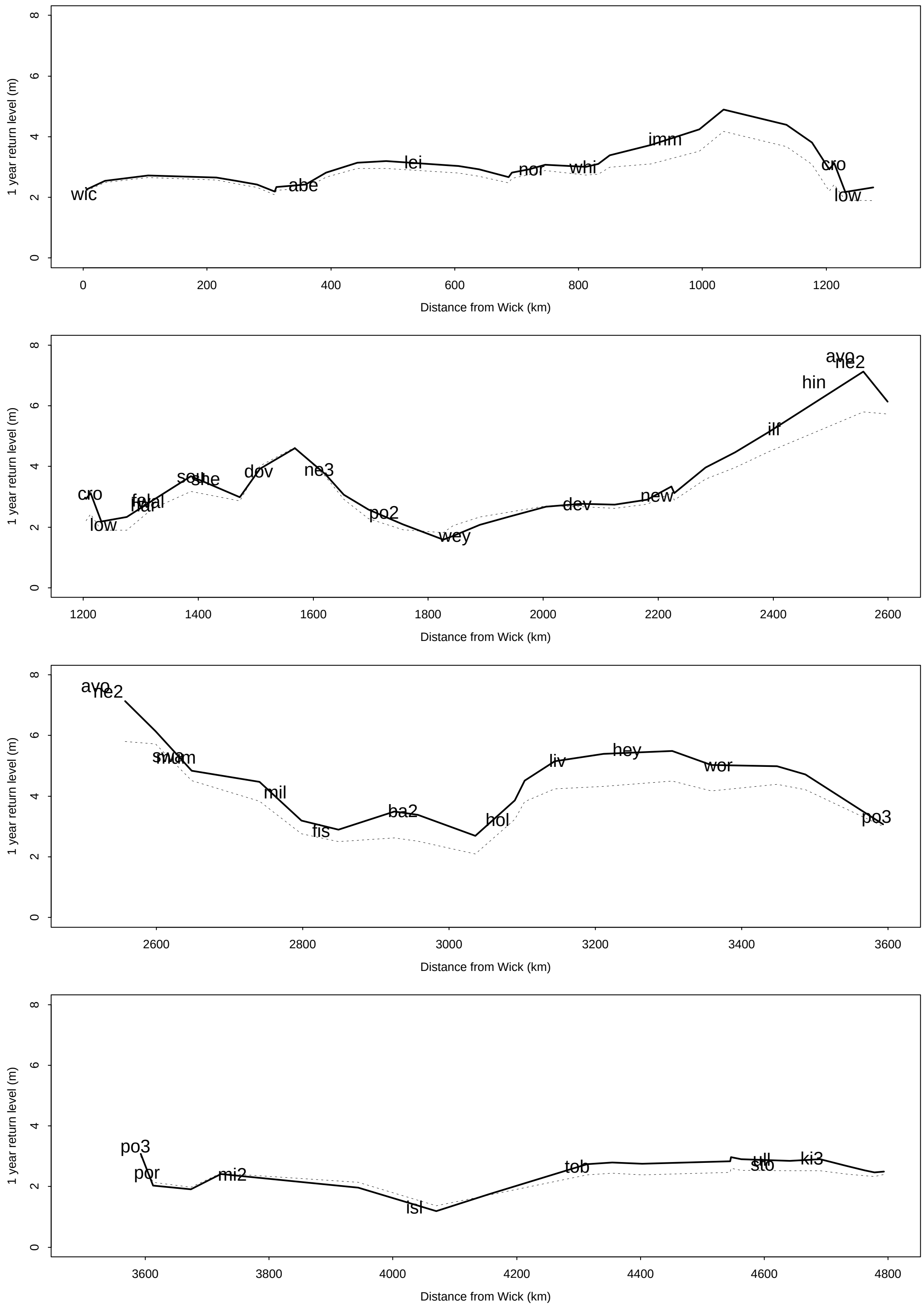

Figure 8.9: Spatial estimate of the 1 year level. The faint broken line is the estimate obtained using the spatial tides. The site names correspond to estimates given by the JPM applied to site data, and the solid line is the calibrated spatial 1 year estimate.

Dist. (km)	1 yr (m)	Dist. (km)	1 yr (m)	Dist. (km)	1 yr (m)
-5	2.26	1276	2.33	2925	3.49
5	2.26	1319	2.86	2957	3.39
35	2.54	1387	3.68	3036	2.69
105	2.72	1472	2.99	3090	3.86
215	2.66	1507	3.92	3103	4.51
247	2.55	1568	4.60	3144	5.16
281	2.42	1621	3.74	3211	5.40
309	2.20	1653	3.07	3305	5.48
312	2.33	1696	2.57	3358	5.02
359	2.42	1756	2.09	3448	4.99
392	2.82	1826	1.59	3487	4.72
443	3.14	1843	1.71	3593	3.07
489	3.19	1890	2.07	3613	2.04
606	3.04	1941	2.35	3674	1.91
639	2.92	2005	2.67	3722	2.41
687	2.67	2066	2.76	3944	1.97
692	2.81	2124	2.74	4070	1.19
720	2.92	2181	2.90	4155	1.75
746	3.08	2223	3.33	4314	2.73
812	3.01	2228	3.12	4354	2.79
832	3.10	2282	3.96	4403	2.75
850	3.39	2334	4.46	4545	2.83
917	3.73	2393	5.14	4546	2.97
995	4.24	2557	7.13	4563	2.90
1034	4.89	2599	6.14	4641	2.85
1136	4.40	2648	4.84	4690	2.90
1177	3.81	2741	4.46	4732	2.68
1205	2.93	2798	3.20	4762	2.54
1213	3.12	2849	2.90	4778	2.47
1231	2.18	2925	3.49	4793	2.49

Table 8.4: Estimated 1 year level against the distance metric around the coast, evaluated using the spatial tidal estimate, corrected for the JPM site estimates.

Site	1 yr level (m)	Site	1 yr level (m)
Wick	2.13	Hinkley	6.78
Aberdeen	2.42	Avonmouth	7.65
Leith	3.17	Newport	7.45
North Shields	2.94	Swansea	5.34
Whitby	3.01	Mumbles	5.29
Immingham	3.94	Milford Haven	4.14
Cromer	3.12	Fishguard	2.87
Lowestoft	2.09	Barmouth	3.52
Felixstowe	2.90	Holyhead	3.22
Harwich	2.73	Liverpool	5.18
Walton on the Naze	2.84	Heysham	5.53
Southend	3.68	Port Erin	3.34
Sheerness	3.60	Workington	5.02
Dover	3.85	Portpatrick	2.46
Newhaven	3.91	Millport	2.40
Portsmouth	2.49	Islay	1.33
Weymouth	1.72	Tobermory	2.66
Devonport	2.76	Stornoway	2.74
Newlyn	3.05	Ullapool	2.90
Ilfracombe	5.24	Kinlochbervie	2.94

Table 8.5: The one year level, in 1990, at the data sites as estimated using the JPM.

8.3 Coastal distance of a site

In this section we illustrate how the distance of a given site can be calculated using Table 4.1. Table 4.1 defines the distance metric around the coast. Conditional on the latitude and longitude, linear interpolation from neighbouring grid points can be used to calculate the distance of a coastal site on this metric.

As an aid to locating a given site on our distance metric, Figures 8.10–8.17 show enlarged maps of the UK with

- the numerical grid points, shown as numbers,
- the nearest coastal location to each grid point, shown as large crosses, and joined by bold continuous lines
- the data sites shown as triangles.

We illustrate how to use Table 4.1 and Figures 8.10-8.17 to locate a site on the metric. For example, consider two sites: one where the coastline is fairly simple, and where the spatial estimate is likely to be good, and one where the coastline is complex, and the spatial estimate is likely to be poor. In particular, we choose North Shields on the east coast and Silloth on the north west coast of England to illustrate a simple and complex coastal region respectively.

The distances are calculated for North Shields as follows:

- Obtain the latitude-longitude position. North Shields has approximate latitude/longitude of (55.01, -1.46) and is shown on the enlarged map, Figure 8.11, as a triangle and site name.
- Locate the two nearest grid points; from Figure 8.11 they are numbers 17 and 18 for North Shields. Note that these are the numbers which correspond to the crosses on the bold line, and not the location of the numbers on the map.
- Estimate the approximate ratio of the distance from each of these two grid points. For example, North Shields is very close to grid point 17, and so the ratio is taken to be 9:1, and this gives corresponding weights of 0.9 and 0.1 for subsequent use.
- Read the distance of each grid point from Table 4.1, and calculate the distance by linear interpolation. For example the distance of North Shields is

$$d = 720 \times 0.9 + 746 \times 0.1 = 723\text{km}$$

For Silloth, the corresponding numbers are

- Obtain the latitude-longitude position. Silloth has approximate latitude/longitude of (55.96, -4.82) and is shown on the enlarged map as a site, Figure 8.16.
- Locate the two nearest grid points; from Figure 8.16 they are numbers 67 and 68 for Silloth.
- Estimate the approximate ratio of the distance from each of these two grid points. For example, Silloth is about half way between the two points, and so the ratio is taken to be 1:1, and the weights are 0.5 and 0.5.
- Read the distance of each grid point from Table 4.1, and calculate the distance by linear interpolation. For example the distance of Silloth is

$$d = 3358 \times 0.5 + 3448 \times 0.5 = 3403\text{km}$$

The distances of the two nearest grid points should be retained as a test for sensitivity of small distance changes on later return level estimation near to the site of interest. For example, many sites in the Solway Firth, the region around Silloth, have similar distances, but may have very different tides, and thus different return levels.

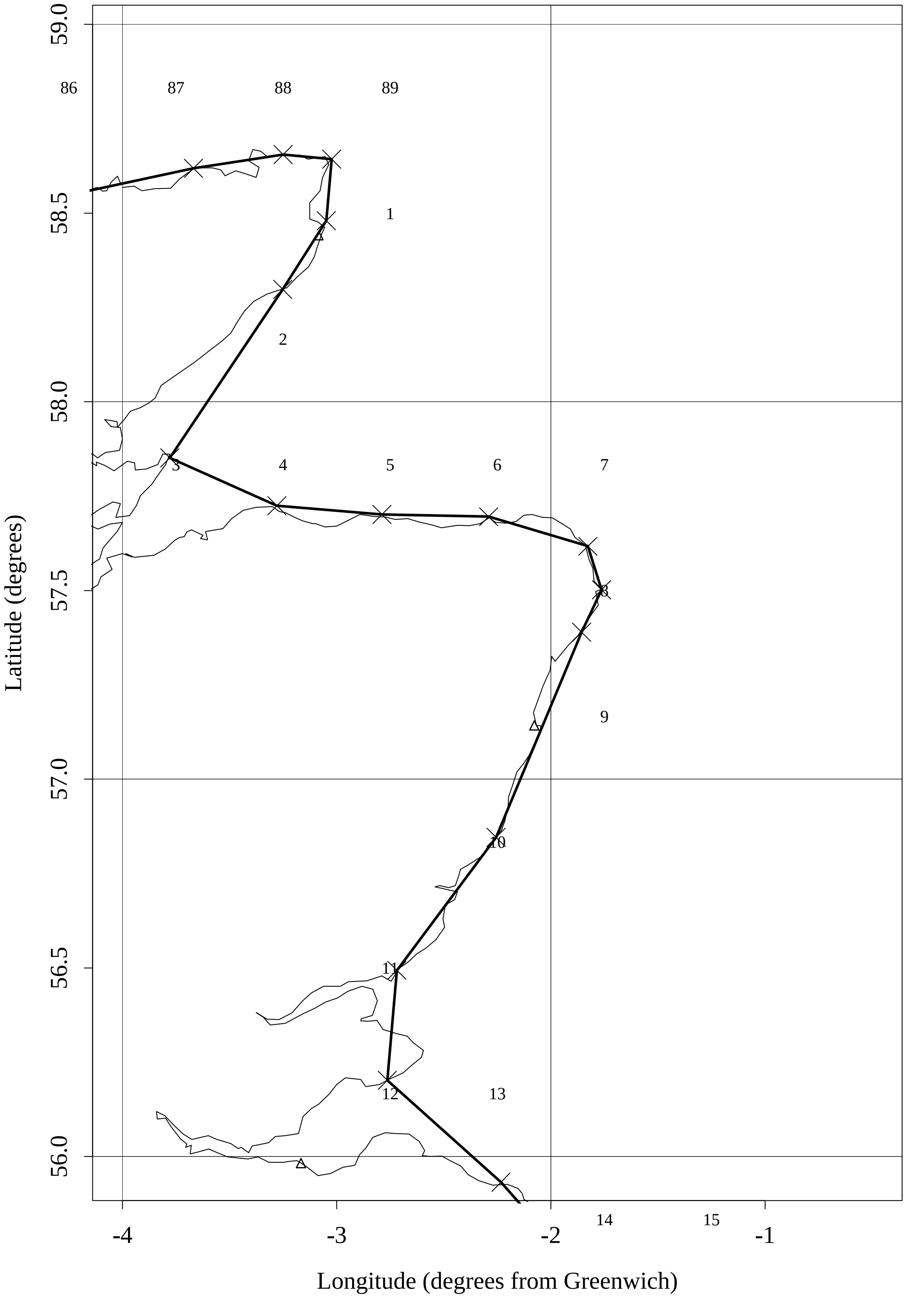

Figure 8.10: Enlarged map number 1 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

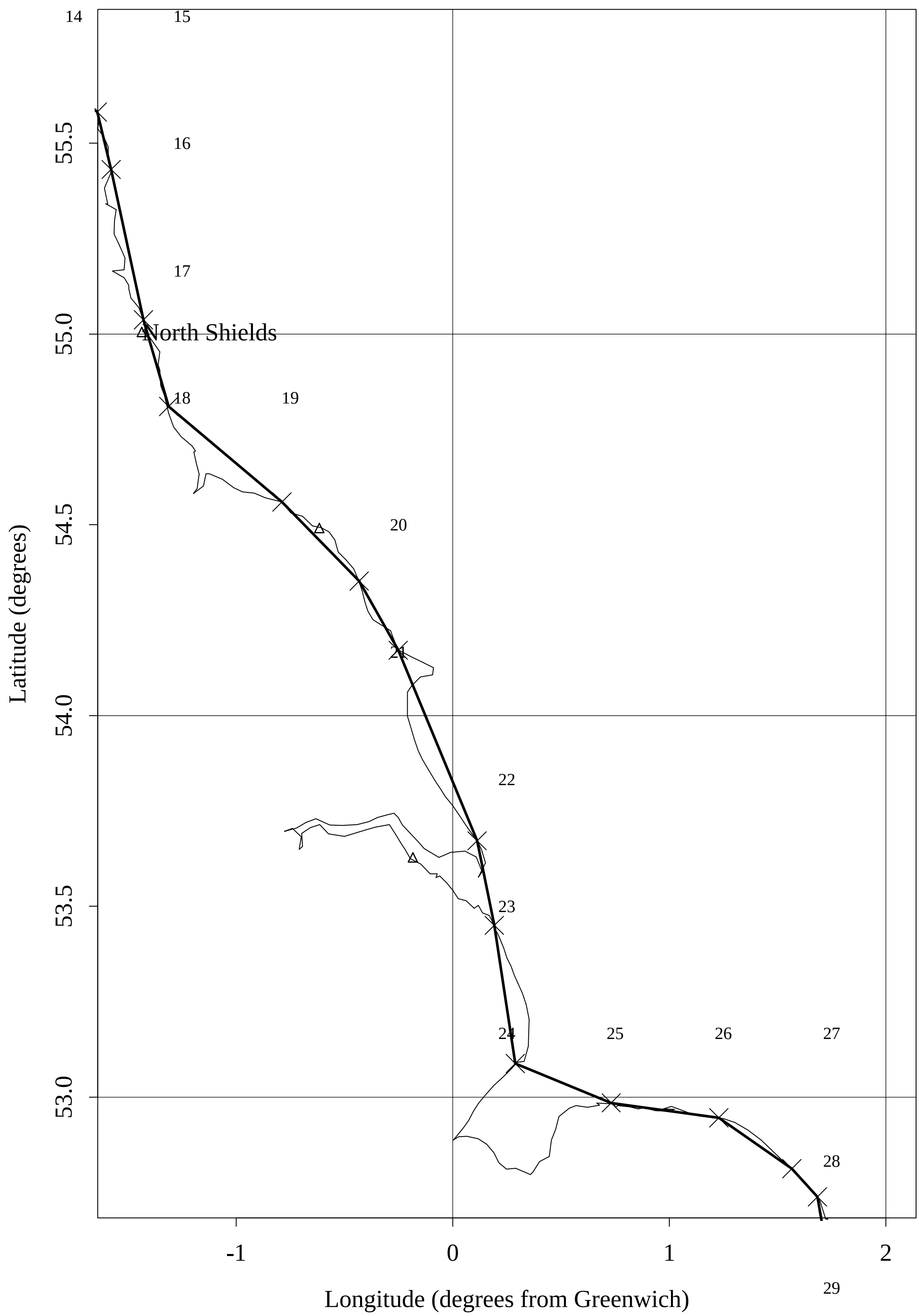

Figure 8.11: Enlarged map number 2 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

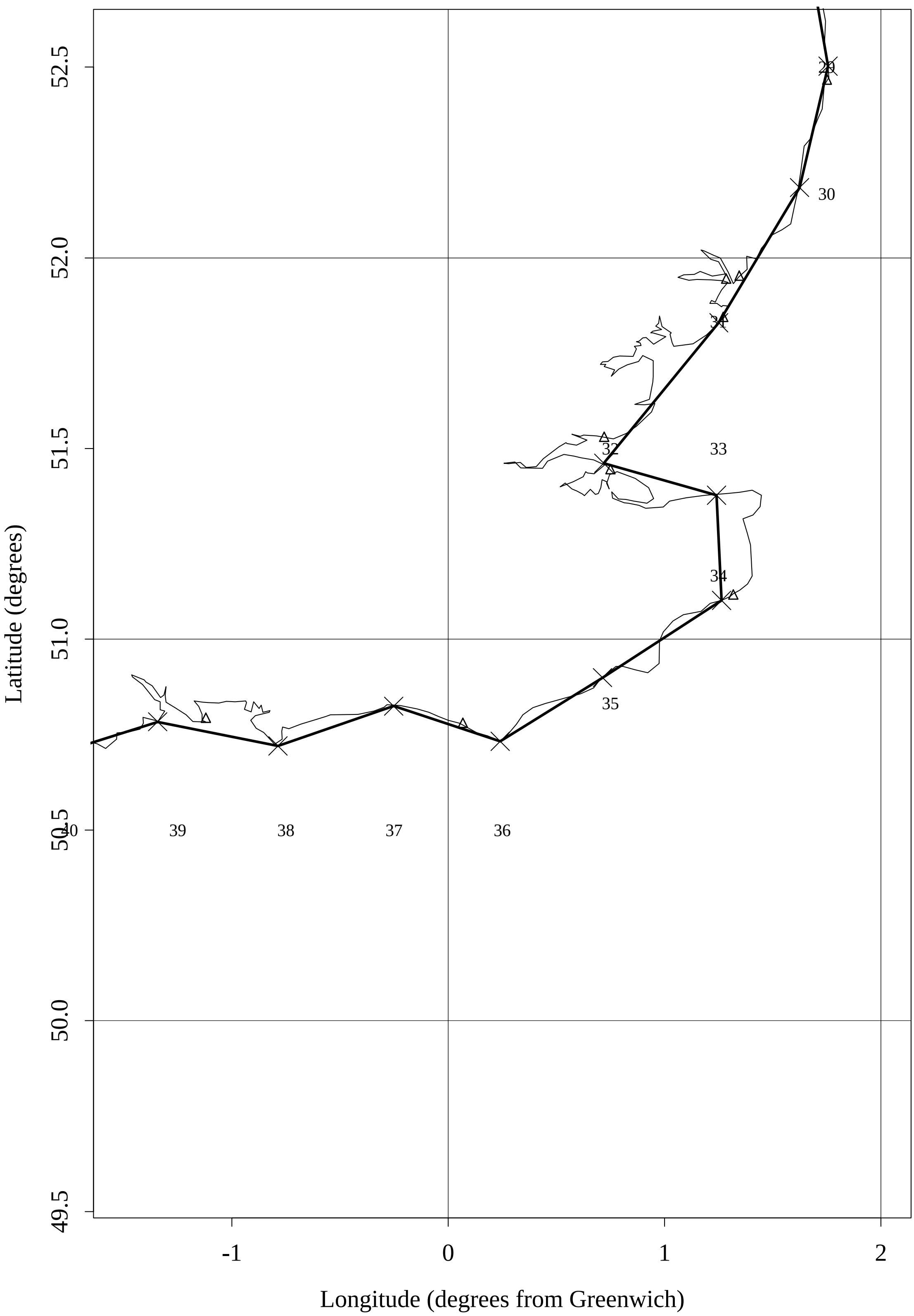

Figure 8.12: Enlarged map number 3 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

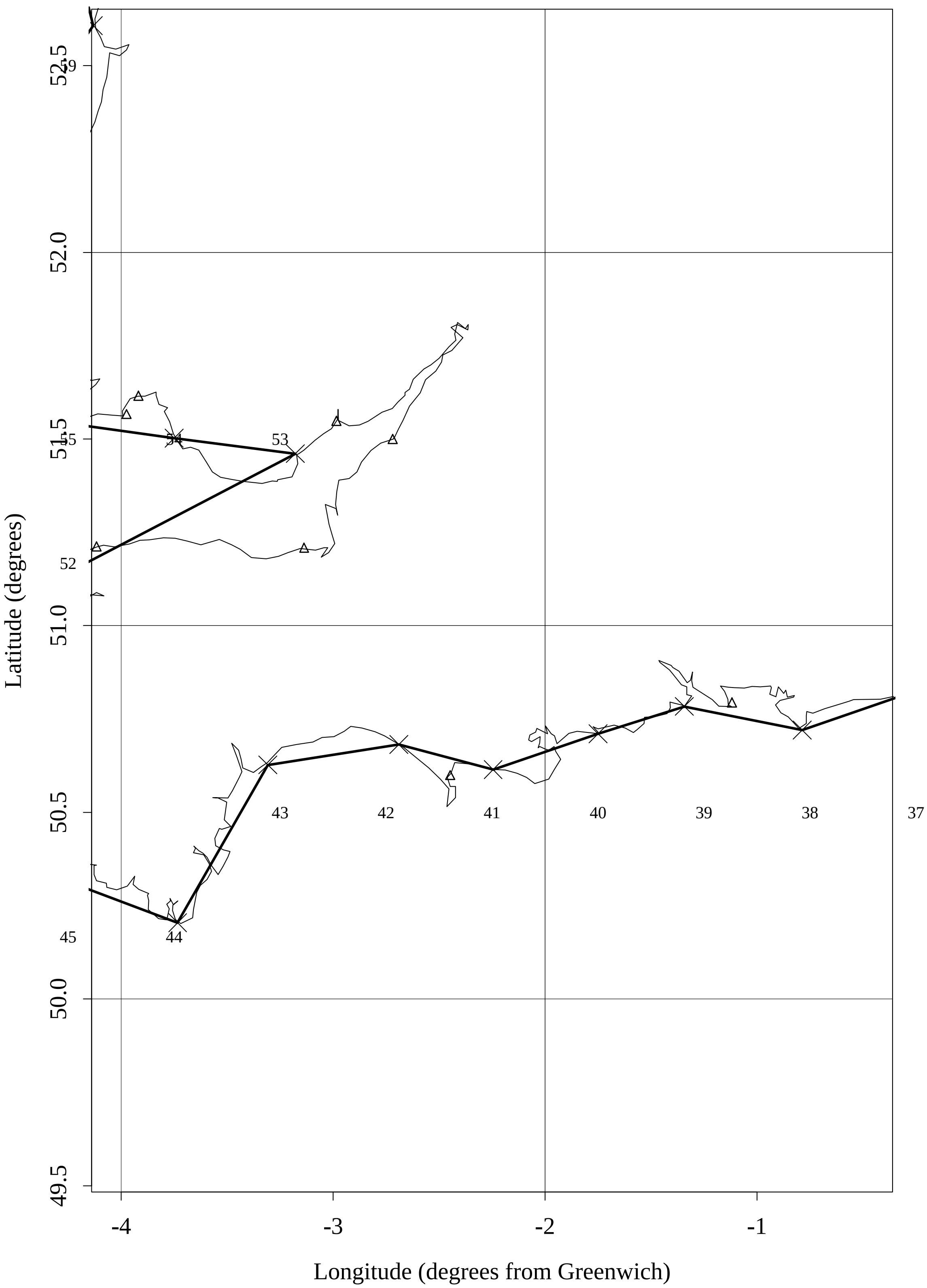

Figure 8.13: Enlarged map number 4 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

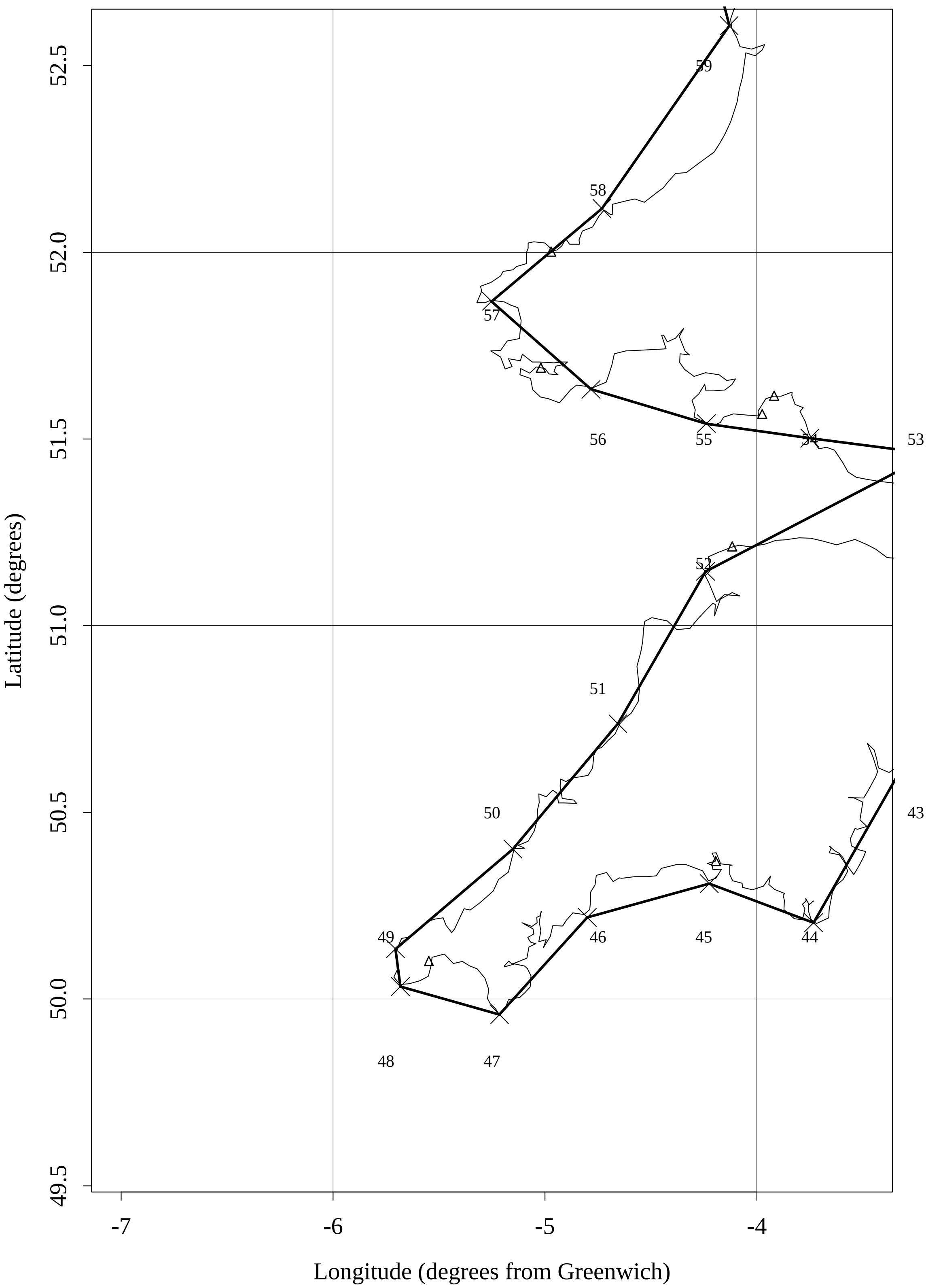

Figure 8.14: Enlarged map number 5 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

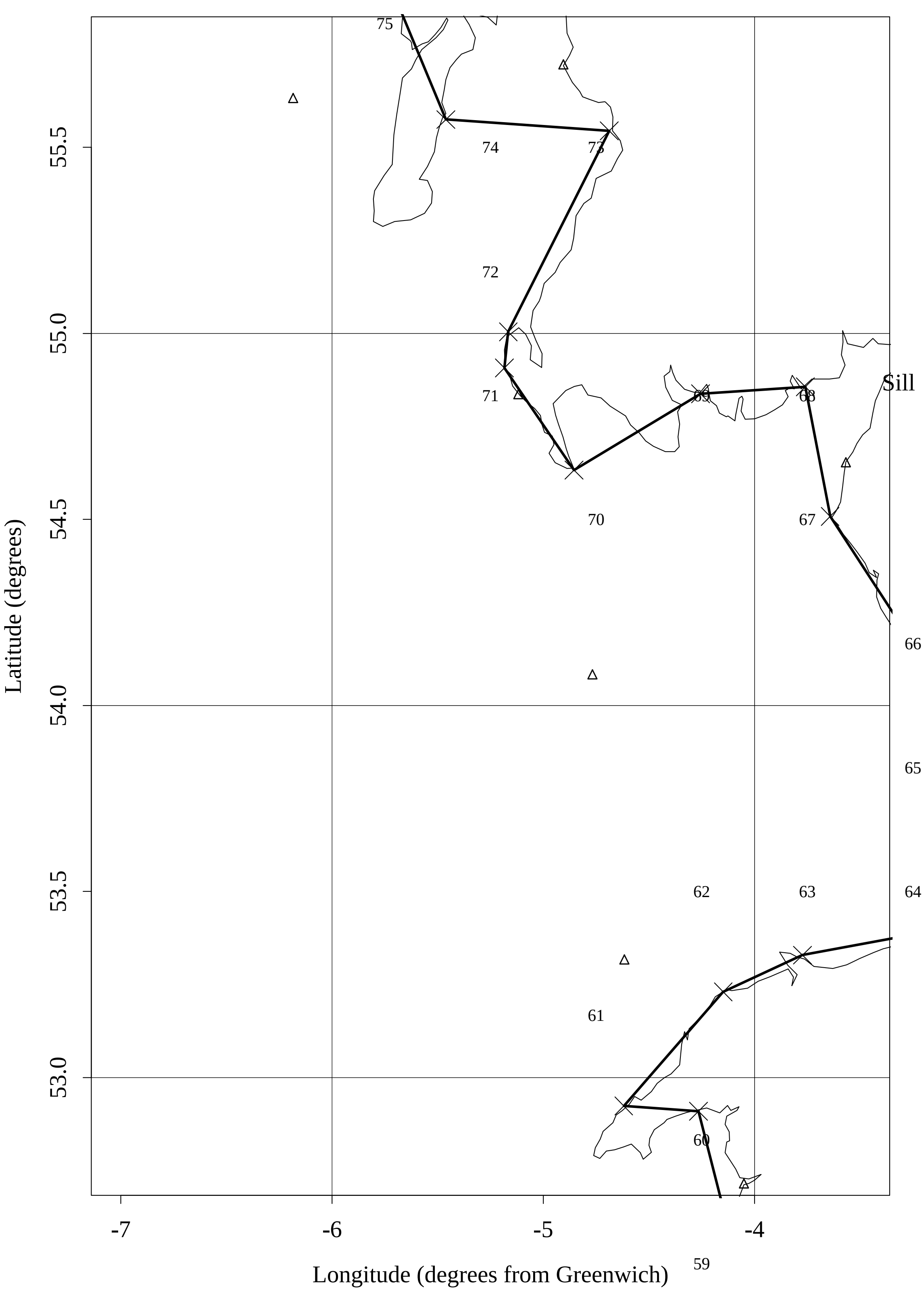

Figure 8.15: Enlarged map number 7 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

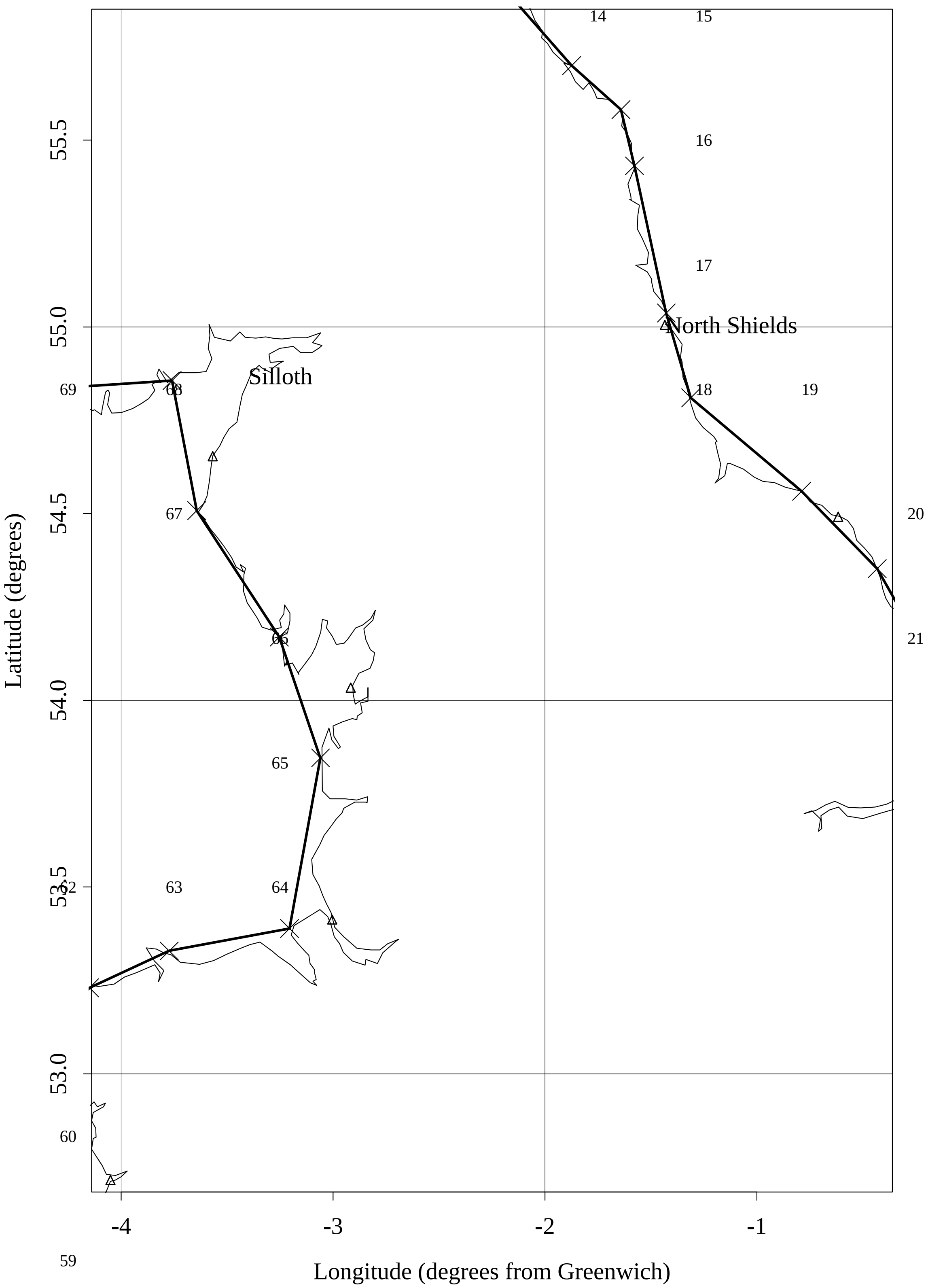

Figure 8.16: Enlarged map number 7 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

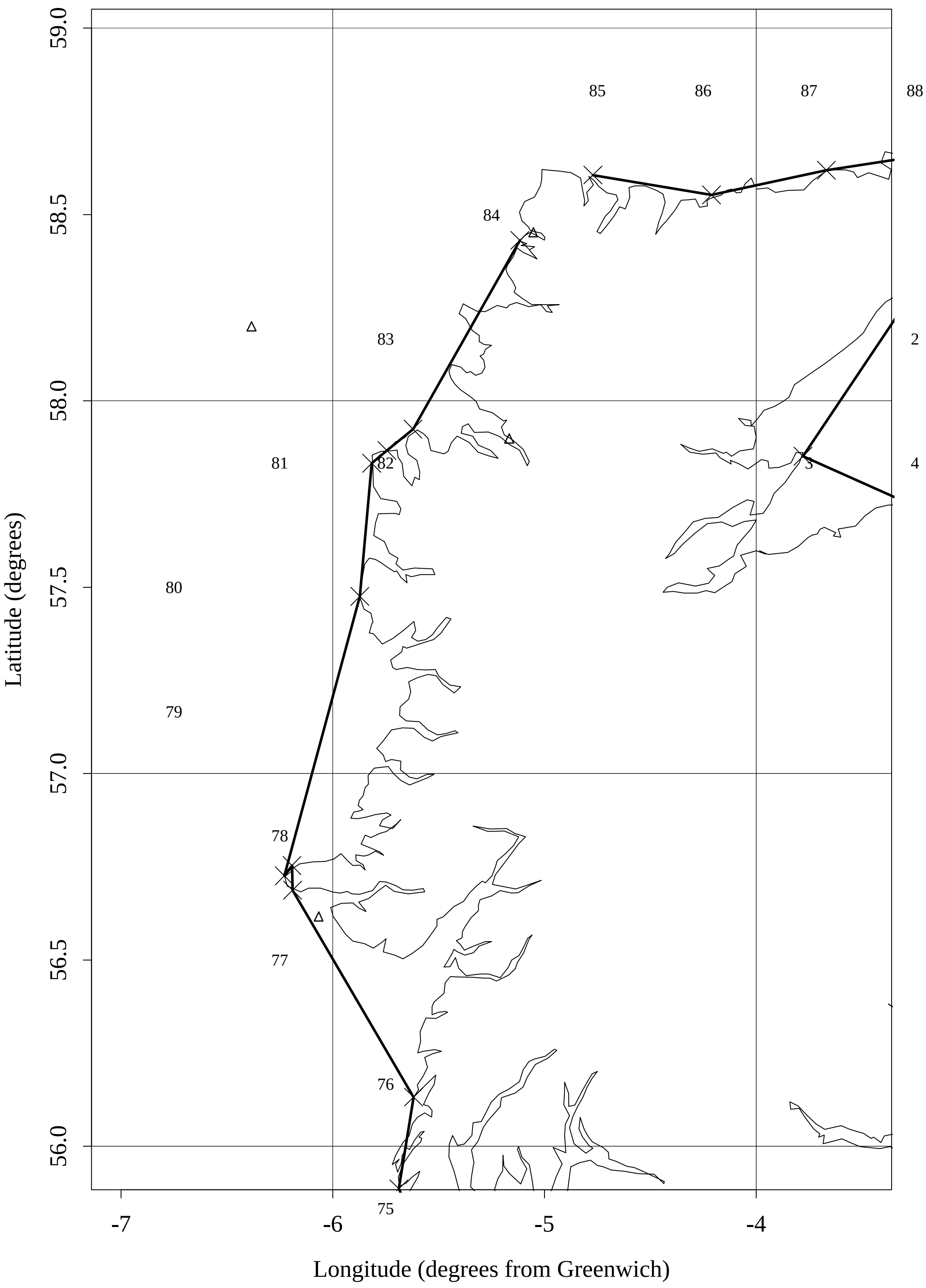

Figure 8.17: Enlarged map number 8 showing an enlarged portion of the UK map, with grid points (numbers), nearest coastal locations to the gridpoints (crosses joined by bold line). Data sites are shown by triangle symbols.

8.4 Datum and Trend Adjustment

In Section 8.2 the spatial estimates of the 1 year return level are given relative to mean sea-level at each location in the year 1990. To obtain return level estimates relative to either ODN or ACD in a year different from 1990 then datum levels and trends have to be accounted for. Thus for a site with distance d, we require

- the estimated trend $\beta(d)$ for the site given by Table 8.7.
- the datum conversion, $DC(d)$, to ODN are given in Table 8.18 for all locations, or to ACD in Table 4.2 for the data sites.

These factors combine to give an adjustment to the return level estimate in year i as

$$\beta(d) \times (i - 1990) + DC(d).$$

8.4.1 Datum levels

Although we have used mean sea-level as the the datum of tidal and surge measurements throughout, from a practical point of view, we may want to relate the estimates to another datum. There are two commonly used datum systems depending on whether the interest is from a nautical or land survey point of view. Admiralty Chart Datum (ACD) is used for the former and is defined as the lowest level to which the sea will fall which approximates to Lowest Astronomical Tide in the UK.

A more appropriate datum for coastal defence is Ordnance Datum Newlyn (ODN). This is established by a land survey and should follow the horizontal surface of the geoid (a surface of constant gravitational potential). There are numerous primary and secondary benchmarks around the UK whose height is known relative to Newlyn. Some of these benchmarks are near tide gauges on the coast and are the datum for sea level measurement known are RLR (Revised Local Reference marks) . Since the RLR levels are known relative to Newlyn then in principal mean sea level, and all other levels of the sea, can be related to Newlyn.

If we were only interested in describing extreme levels at primary tide gauge sites then the information already available would be entirely sufficient. As we are interested in producing estimates for any point on the coast then it is necessary to know how mean sea level relates to ODN as a continuous surface. Figure 8.18, which contains the values of mean sea level relative to ODN around the coastline, shows the difficulty in achieving this.

Mean sea level is not the undisturbed level of the sea. It has contributions from non-linear tidal interactions, from storm surges, from surface waves and from steric effects. Hence the values of mean sea level obtained from the numerical model used in this study, which does not include all these effects, is different by a few tens of centimetres from the observed values.

Added to this is the fact that land levelling is not as accurate over 1000km as it is over 100km. This gives an apparent rise in mean sea level of 30cm between the south coast and the north of Scotland which cannot be seen in the numerical models. There is a drop in mean sea level of some 20 cm over the short distance between Immingham and the Wash

8.4.2 Spatially estimating the datum level

To obtain a continuous surface for the UK coastline the approach adopted was to fit the available values of mean sea-level relative to ODN with a smooth function of the coastal distance metric. Although this does not guarantee that the curve passes through the measured values, these values are themselves statistical variables derived from a regression of the mean and sea-level slope against the observed data. Thus we obtain a value for mean sea level at an arbitrary point along the coastline by smoothing the site-by-site values, and this is given in Table 8.6 and Figure 8.18.

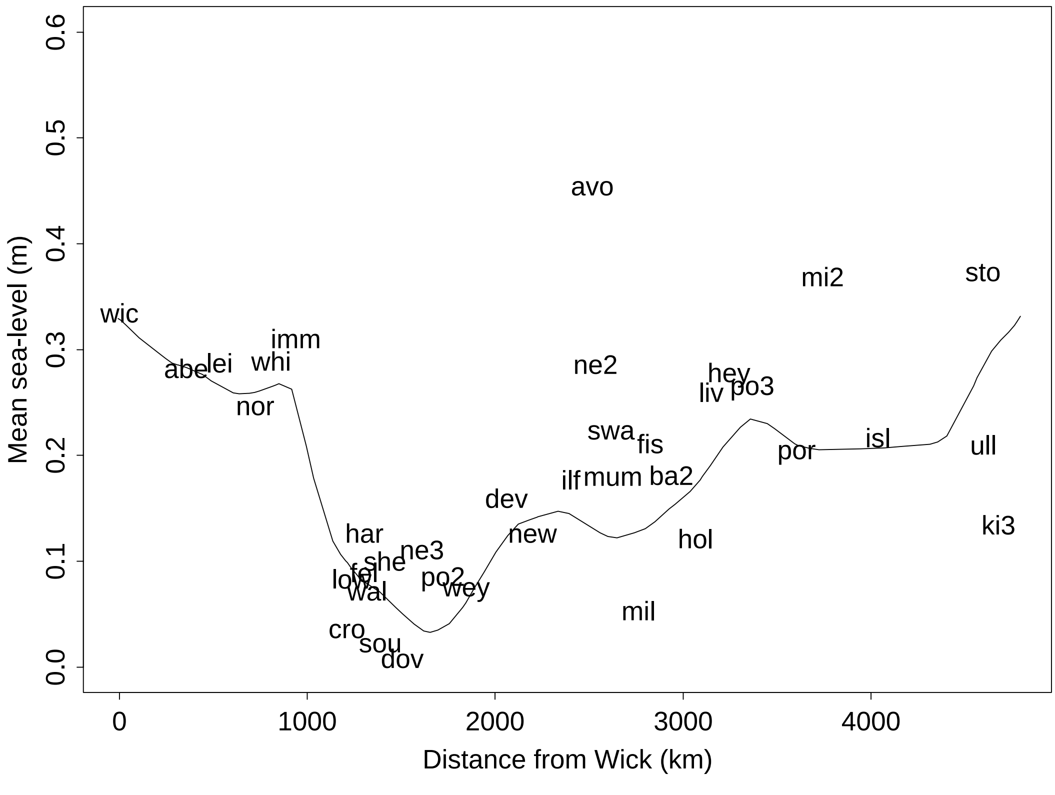

Figure 8.18: Mean sea-level in 1990 relative to ODN plotted against distance from Wick in km.

Dist. (km)	Adjustment	Dist. (km)	Adjustment	Dist. (km)	Adjustment
-5	0.33	1231	0.09	2849	0.14
-5	0.33	1276	0.08	2925	0.15
5	0.33	1319	0.08	2957	0.15
35	0.32	1387	0.07	3036	0.17
105	0.31	1472	0.06	3090	0.18
215	0.30	1507	0.05	3103	0.18
247	0.29	1568	0.04	3144	0.19
281	0.29	1621	0.03	3211	0.21
309	0.29	1653	0.03	3305	0.23
312	0.29	1696	0.03	3358	0.23
359	0.28	1756	0.04	3448	0.23
392	0.28	1826	0.06	3487	0.23
443	0.28	1843	0.06	3593	0.21
489	0.27	1890	0.07	3613	0.21
606	0.26	1941	0.09	3674	0.21
639	0.26	2005	0.11	3722	0.21
687	0.26	2066	0.12	3944	0.21
692	0.26	2124	0.13	4070	0.21
720	0.26	2181	0.14	4155	0.21
746	0.26	2223	0.14	4314	0.21
812	0.27	2228	0.14	4354	0.21
832	0.27	2282	0.14	4403	0.22
850	0.27	2334	0.15	4545	0.27
917	0.26	2393	0.15	4546	0.27
995	0.21	2557	0.13	4563	0.27
1034	0.18	2599	0.12	4641	0.30
1136	0.12	2648	0.12	4732	0.32
1177	0.11	2741	0.13	4762	0.32
1205	0.10	2798	0.13	4778	0.33
1213	0.10	2849	0.14	4793	0.33

Table 8.6: Table of the spatial ODN to MSL adjustment in metres, DC(d), for each distance around the coast.

Dist. (km)	Trend (mm/yr)	Dist. (km)	Trend (mm/yr)	Dist. (km)	Trend (mm/yr)
-5	3.28	1276	1.71	2925	1.97
5	3.24	1319	1.88	2957	2.53
35	2.98	1387	2.08	3036	3.01
105	2.25	1472	2.24	3090	3.06
215	1.23	1507	2.28	3103	3.07
247	1.10	1568	2.17	3144	3.11
281	0.96	1621	1.74	3211	3.07
309	0.86	1653	1.47	3305	2.63
312	0.85	1696	1.22	3358	2.11
359	0.74	1756	1.03	3448	0.34
392	0.72	1826	1.10	3487	-0.02
443	0.75	1843	1.18	3593	-0.22
489	0.83	1890	1.79	3613	-0.24
606	1.37	1941	2.81	3674	-0.29
639	1.58	2005	2.80	3722	-0.33
687	1.85	2066	1.79	3944	-0.97
692	1.87	2124	1.47	4070	-0.17
720	2.02	2181	1.41	4155	1.71
746	2.15	2223	1.51	4314	3.45
812	2.39	2228	1.53	4354	3.50
832	2.43	2282	1.91	4403	3.51
850	2.45	2334	2.57	4545	3.50
917	2.42	2393	3.05	4546	3.50
995	2.43	2557	0.20	4563	3.50
1034	2.51	2599	-0.01	4641	3.47
1136	2.23	2648	-0.04	4690	3.42
1177	1.89	2741	0.17	4732	3.33
1205	1.69	2798	0.48	4762	3.22
1213	1.68	2849	0.89	4778	3.10
1231	1.64	2925	1.97	4793	2.99

Table 8.7: Spatial trend estimate for each distance around the coast.

8.5 Worked Examples

To illustrate how the estimates in this report can be used in this section we obtain the return level estimates at Silloth and North Shields. Specifically, consider the estimation of the 100 year return level at the two sites for the year for 2010.

The estimates are obtained using the six step procedure below. We subsequently index Silloth and North Shields by 1 and 2 respectively.

- Calculate the distance of the two nearest grid points of the latitude-longitude on our distance metric as in the previous section. Thus

$$d_{1,1} = 3358, d_{1,2} = 3448, d_{2,1} = 720, d_{2,2} = 746.$$

- Calculate the 1 year level. As discussed *this is best done using a year or more of data from the site of interest.* However if this is not available, then using the distances obtained in the previous section, calculate the 1 year level from Table 8.4. Thus, assuming no information *at all* is available from the sites,

$$z_1(d_{1,1}) = 5.02, z_1(d_{1,2}) = 4.99, z_1(d_{2,1}) = 2.92, z_1(d_{2,2}) = 3.08$$

- Calculate the 100 year return level adjustment from Tables 8.1-8.3. Thus,

$$D_{100}(d_{1,1}) = 0.91, D_{100}(d_{1,2}) = 0.85, D_{100}(d_{2,1}) = 0.71, D_{100}(d_{2,2}) = 0.76.$$

- Calculate the additive trend adjustment based on the distance. This is achieved by calculating the trend from Table 8.7, i.e.

$$\beta(d_{1,1}) = 2.11, \beta(d_{1,2}) = 0.34$$

$$\beta(d_{2,1}) = 2.02, \beta(d_{2,2}) = 2.15$$

  and then forming the adjustment using

$$(2010 - 1990) \times \beta(d_{1,1}) \times 10^{-3} = 0.04m, (2010 - 1990) \times \beta(d_{1,2}) \times 10^{-3} = 0.01m$$

$$(2010 - 1990) \times \beta(d_{2,1}) \times 10^{-3} = 0.04m, (2010 - 1990) \times \beta(d_{2,2}) \times 10^{-3} = 0.04m$$

  Note that the large difference in trend estimate at the two points nearest to Silloth is due to the limited spatial density of sites around this part of the coastline (see Figure 5.4).

- Depending on the datum to which the return level is required, form a datum adjustment, DC.

  - If MSL datum is required, then no adjustment is required, i.e $DC(d) = 0$.

  - If ODN datum is required, then a table in Section 8.4 will give the adjustment based on the distance of the site. Here we have

$$DC(d_{1,1}) = 0.26, DC(d_{1,2}) = 0.24, DC(d_{2,1}) = 0.25, DC(d_{2,2}) = 0.25$$

  - If ACD datum is required at a particular data site, then Table 4.2 (page 58) can be used.

- The return level relative to the required datum is then given by linear interpolation of the two values. If the two values differ substantially, the resulting estimate should be treated with caution. For example in our examples, the ratio of the distance to each site are 1:1 and 9:1. Thus the weights are 0.5,0.5, and 0.9,0.1, and we get

$$z_{100}(d_{1,1}) = [5.02 + 0.91 + 0.04] = 5.97m$$

$$z_{100}(d_{1,2}) = [4.99 + 0.85 + 0.04] = 5.88m$$

$$z_{100}(d_{2,1}) = [2.92 + 0.71 + 0.04] = 3.67m$$

$$z_{100}(d_{2,2}) = [3.08 + 0.76 + 0.04] = 3.88m$$

Thus the 100 year level at the example sites is

$$z_{100}(d_1) = 0.5 \times 5.97 + 0.5 \times 5.88 = 5.92m$$

$$z_{100}(d_2) = 0.9 \times 3.67 + 0.1 \times 3.88 = 3.69m$$

And to ODN, the 100 year level is

$$z_{100}(d_1) = 5.92 + 0.5 \times 0.26 + 0.5 \times 0.24 = 6.17m$$

$$z_{100}(d_2) = 3.69 + 0.9 \times 0.25 + 0.1 \times 0.25 = 3.94m$$

8.6 Comparisons with annual maximum data estimates

Results in this section are all quoted to ODN, which is consistent with Coles and Tawn (1990). In this section we compare the estimates obtained in this report with those obtained in Coles and Tawn (1990), where long term historical annual maximum data was used. The comparisons are made with the Coles and Tawn marginal estimates unless stated otherwise. This serves as an independent assessment of how well our spatial methods are working at low return periods at many additional sites to those which we have analysed in this report. The annual maximum data contain accurate information at low return levels, although the annual maximum method may perform poorly at higher return levels (see DT1). In particular, the one year level is estimated well at each of the 62 sites in Coles and Tawn (1990).

Figure 8.19 displays the 1 year level plotted against distance for each of the annual maximum sites. Also shown on the plot is the spatial one year estimate derived in Section 8.2, and the estimates at the hourly data sites from the JPM. This figure emphasises how rapidly the one year level can change in some complex coastal regions, and serves as a warning that our spatial estimate of the one year level may be poor at places like inlets and estuaries. In particular, the following regions are poorly estimated:

- Humber estuary
- Thames estuary,
- Severn Estuary,
- Hilbre Island and Silloth

Figure 8.20 shows the 100 year return level relative to the one year level for the AMM (from Coles and Tawn, 1990) and from our spatial estimate. Within the errors of the annual maximum estimates, our spatial estimate is consistent with these estimates for nearly all of the coastline.

Finally, Table 8.8 shows the Coles and Tawn (1990) marginal and spatial estimate of the 10 year return level for those annual maximum sites, and our spatial estimate. This table should not be treated as an updated table of return level estimates at these sites; it is included to show:

- a warning that our spatial estimate can sometimes be very poor, such as up estuaries and inlets.
- in general, the spatial estimate appears to agree closely with the annual maximum estimates.

Tables of the 100 and 1000 year levels are given in the Appendix (see Tables 13.7–13.10; pages 214–217).

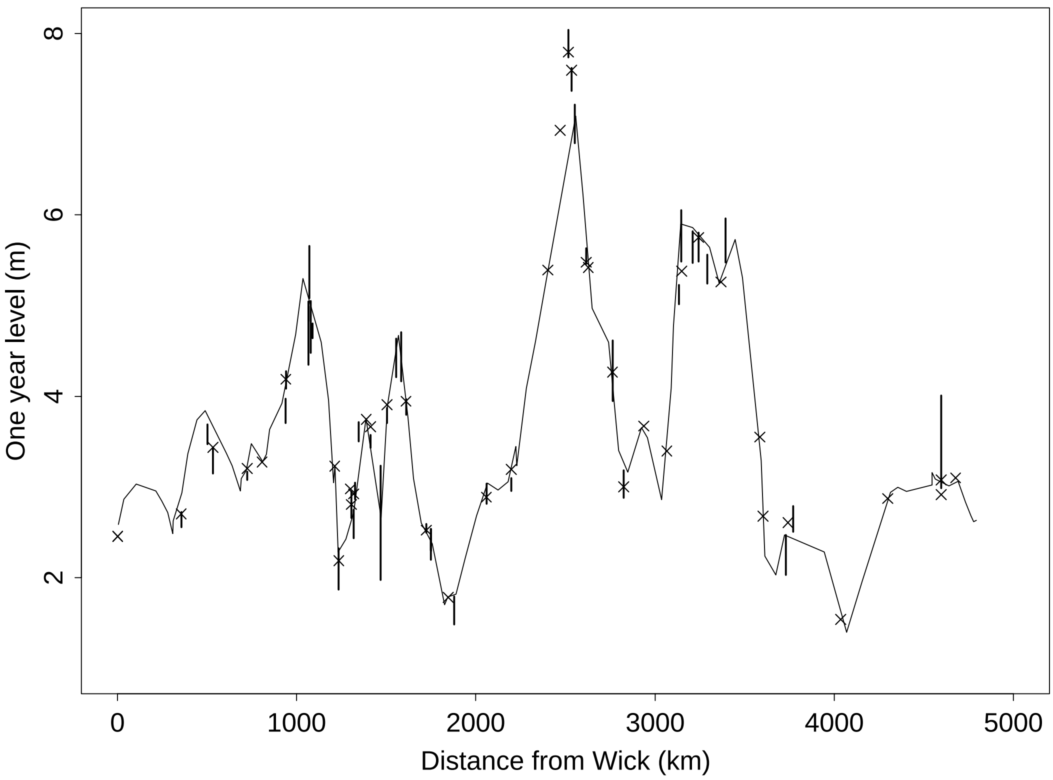

Figure 8.19: One year level plotted against distance. The solid line is the spatial estimate, the broken line is the unadjusted estimate, the solid bars are AMM 95% confidence intervals of the one year level estimate, and the crosses are hourly data site estimates from the JPM.

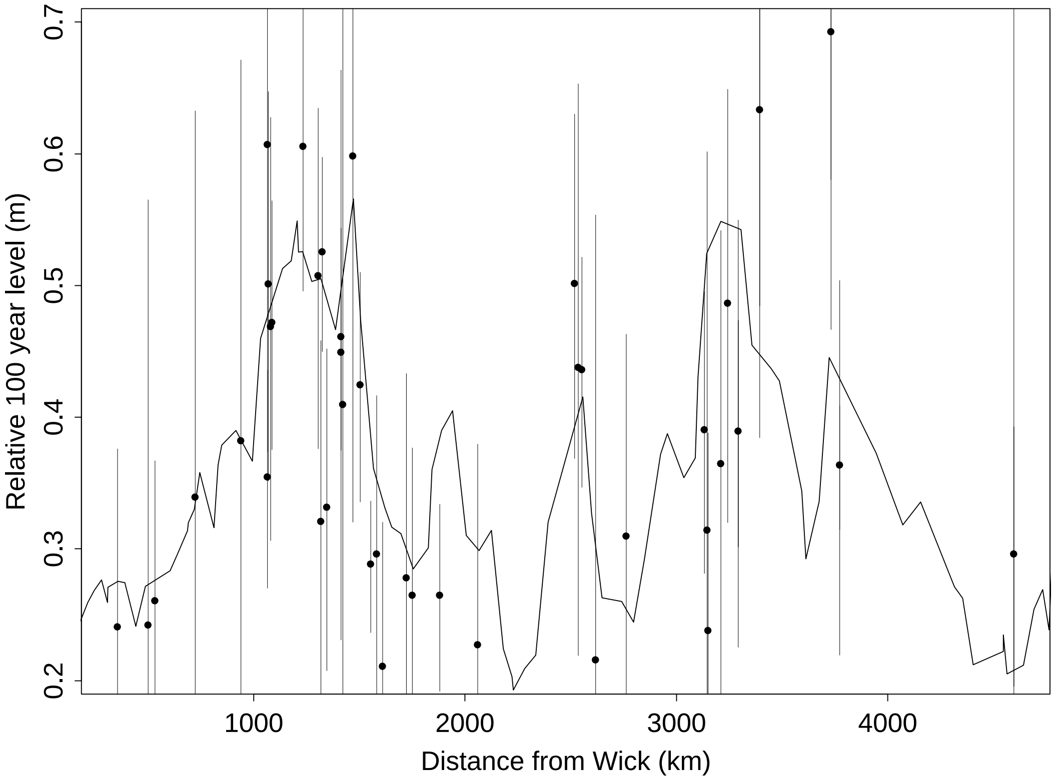

Figure 8.20: 100 year return level relative to the 1 year level, plotted against distance. The names and 95% confidence intervals lines are for the annual maximum method, and the solid line is the **Approach IV** spatial estimate. The confidence intervals are those of the 100 year return level and are shown as a guide only.

Site	nyr	CT90 Marg	se	CT90 Spat	se	Method IV
Ullapool	12	3.79	0.29	3.96	0.07	3.37
Gourock	56	3.01	0.08	3.07	0.05	2.95
Ardrossan	35	2.94	0.36	2.70	0.05	3.04
Silloth	40	6.35	0.13	6.15	0.05	5.69
Barrow	19	5.79	0.13	5.86	0.05	6.24
Heysham	36	6.13	0.13	6.11	0.05	6.19
Fleetwood	48	6.01	0.08	5.99	0.03	6.15
Hilbre Island	80	5.51	0.06	5.50	0.03	5.66
Princes Pier	37	6.10	0.14	6.13	0.04	5.89
Georges Pier	42	5.82	0.27	5.82	0.03	5.90
Gladstone Dock	20	6.08	0.14	6.07	0.04	5.88
Eastham Lock	19	6.43	0.06	6.42	0.03	5.90
Fishguard	16	3.23	0.06	3.22	0.03	3.44
Milford Haven	26	4.59	0.17	4.31	0.03	4.36
Swansea	36	5.76	0.03	5.79	0.03	6.09
Cardiff	41	7.44	0.11	7.45	0.04	7.61
Newport	37	7.93	0.08	7.88	0.04	7.39
Avonmouth	61	8.39	0.09	8.35	0.04	7.17
Newlyn	61	3.20	0.04	3.23	0.02	3.44
Devonport	38	3.15	0.07	3.14	0.02	3.18
Portland	20	1.90	0.08	1.84	0.03	2.45
Calshot	42	2.49	0.06	2.54	0.02	2.47
Southampton	47	2.68	0.07	2.69	0.02	2.47
Portsmouth	104	2.82	0.04	2.82	0.02	2.69
Newhaven	60	4.09	0.05	4.14	0.02	4.29
Pevensey	24	4.73	0.14	4.70	0.03	4.75
Rye	4	4.71	0.13	4.72	0.04	4.88
Dover	62	4.21	0.08	4.23	0.03	4.40
Margate	10	3.20	0.52	3.06	0.05	3.63
Southend	57	4.01	0.09	2.69	0.02	2.47

Table 8.8: Estimates of the 10 year return level, in metres, to ODN, for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method.

Site	nyr	CT90 Marg	se	CT90 Spat	se	Method IV
Sheerness	136	3.95	0.06	3.92	0.03	4.03
Tilbury	46	4.55	0.12	4.51	0.03	4.03
Tower Pier	49	5.21	0.10	5.20	0.03	3.97
Colchester	43	3.94	0.07	4.02	0.04	3.75
Holland-on-Sea	53	3.48	0.12	3.41	0.05	3.52
Walton-on-the-Naze	15	2.91	0.13	3.07	0.05	3.44
Harwich	51	3.31	0.11	3.28	0.04	3.28
Lowestoft	31	2.70	0.17	2.53	0.04	2.81
Gt. Yarmouth	77	2.51	0.11	2.37	0.04	3.18
Kings Lynn	119	5.19	0.06	5.20	0.04	5.26
Wisbech Cut	22	5.23	0.19	5.20	0.05	5.30
Marsh Road Sluice	17	5.87	0.22	5.81	0.05	5.35
Lawyers Sluice	26	5.27	0.23	5.14	0.04	5.37
Boston	59	5.29	0.07	5.39	0.04	5.38
Grimsby	54	4.02	0.11	4.22	0.04	4.50
Immingham	69	4.56	0.06	4.55	0.04	4.51
Saltend Jetty	13	5.06	0.25	4.95	0.03	4.35
Humber Dock	42	4.76	0.11	4.75	0.03	4.37
St. Andrews Dock	49	4.95	0.07	4.99	0.03	4.38
Victoria Dock	24	4.88	0.12	4.85	0.03	4.37
King Georges Dock	36	4.74	0.09	4.75	0.03	4.35
Blacktoft	56	5.45	0.07	5.45	0.03	4.44
Brough	56	5.35	0.07	5.36	0.03	4.40
Goole	59	5.75	0.06	5.75	0.03	4.49
North Shields	35	3.46	0.14	3.53	0.05	3.54
Kirkcaldy	28	3.42	0.10	3.40	0.03	3.70
Methil	38	3.82	0.07	3.85	0.03	3.72
Leith	38	3.55	0.08	3.54	0.03	3.67
Rosyth	31	3.77	0.08	3.80	0.04	3.67
Grangemouth	34	4.02	0.11	3.97	0.05	3.65
Aberdeen	67	2.88	0.05	2.89	0.03	2.98

Table 8.9: Estimates of the 10 year return level, in metres to ODN, for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method.

Chapter 9

Complex coastal regions

In this chapter, we extend the methods of previous chapters to improve estimation around regions of the coast which have complex bathymetry and coastline structure. Using the low resolution 36km model, we have seen how the numerical model data can be used to improve return level estimates. We have found that tidal characteristics can sometimes change very rapidly along a coastline, and we have quoted results relative to the one year level in order to emphasise this.

For simple coastlines, we have found that the 36km model (with the 12km tidal information) leads to adequate estimates of the tidal characteristics and hence acceptable return level estimates. Within complex coastal regions the tide changes so rapidly from point to point that this numerical grid resolution is inadequate to describe the spatial behaviour of the extreme levels between grid points. For example, in Chapter 8 we saw how the estimated one-year return level could be mapped well for most of the coastline, but that it was particularly poorly estimated in a few regions. Using the Bristol Channel and Severn estuary region as an example, we show how fine-resolution numerical model output can be used to improve return level estimates.

Other regions for which fine resolution numerical model output is required are

- Humber estuary and the Wash
- Southern North Sea and Thames estuary
- Solent
- Morecambe Bay.

Models for these regions will be run, and results derived after the completion of this project. The estimates obtained previously in this report for sites in these complex coastal regions, and for other inlet or estuarine regions should be treated with caution. The methods described in this chapter aim to produce estimates that are substantially more reliable.

The chapter is structured as follows. In Section 9.1 we describe the high resolution numerical model data, and use it to obtain the one year return level at each point along the estuary. In

Sections 9.2 to 9.4 we give results that, in combination with the one year return level estimates from Section 9.1, enable calculation of return level estimates for any return period in the same way as in Chapter 8. The tables are in the same format as in Chapter 8, and calculation of different return level estimates to a specific year and datum proceeds as in the examples in Section 8.5. We define a new distance metric in Section 9.1 for the Severn Estuary, which is used in place of the UK metric defined in Chapter 4. In Sections 9.2 to 9.4 results for relative return levels, trends, and ODN conversion respectively are given. Combination of these features gives any return level at all points along the estuary. Finally in Section 9.5 we give a comparison of the results with annual maximum estimates given by Coles and Tawn (1990).

Throughout, we use abbreviations BC (BCM) and SE (SEM) to denote the Bristol Channel (Model) and Severn Estuary (Model) respectively.

9.1 Bristol Channel and Severn Estuary regions

For the Bristol Channel and Severn Estuary regions, numerical model data are available at resolutions of 4km and 1.3km data respectively. Figure 9.1 shows the grid locations of the available data. We have defined an alternative distance metric for presentation of results for this region. Tables 9.1 and 9.2 give the latitude, longitude and corresponding distances (in km) along the estuary from the first grid point located near to model point 51 on the southern coast of the estuary.

The distance of any site can be located by linear interpolation of the two closest grid points in the same way as for the UK main coastline in Chapter 4.

9.1.1 Data span selection

In contrast to the low resolution 36km model data, for which 39 years of synthetic data are available, it is only feasible to run the high resolution numerical models for a shorter continuous time span of 5 years. Thus the first step is to determine a suitable span of 5 years that will be representative of the data over a longer period. After some experimentation, we chose to obtain numerical model data for the span 1981-1985. One check on the suitability of this data span is given in Figure 9.2. This figure shows the 1 year return level estimated using the JPM on two data sets for a selection of the 36km grid points. In particular, Figure 9.2 shows estimates using the data sets are for the full 39 year period plotted against estimates obtained using the 1981-1985 reduced period. It is seen that there is very little differences between the two, which suggests that we are able to get accurate and representative estimates of the one year return level from just the 5 years of data 1981-1985.

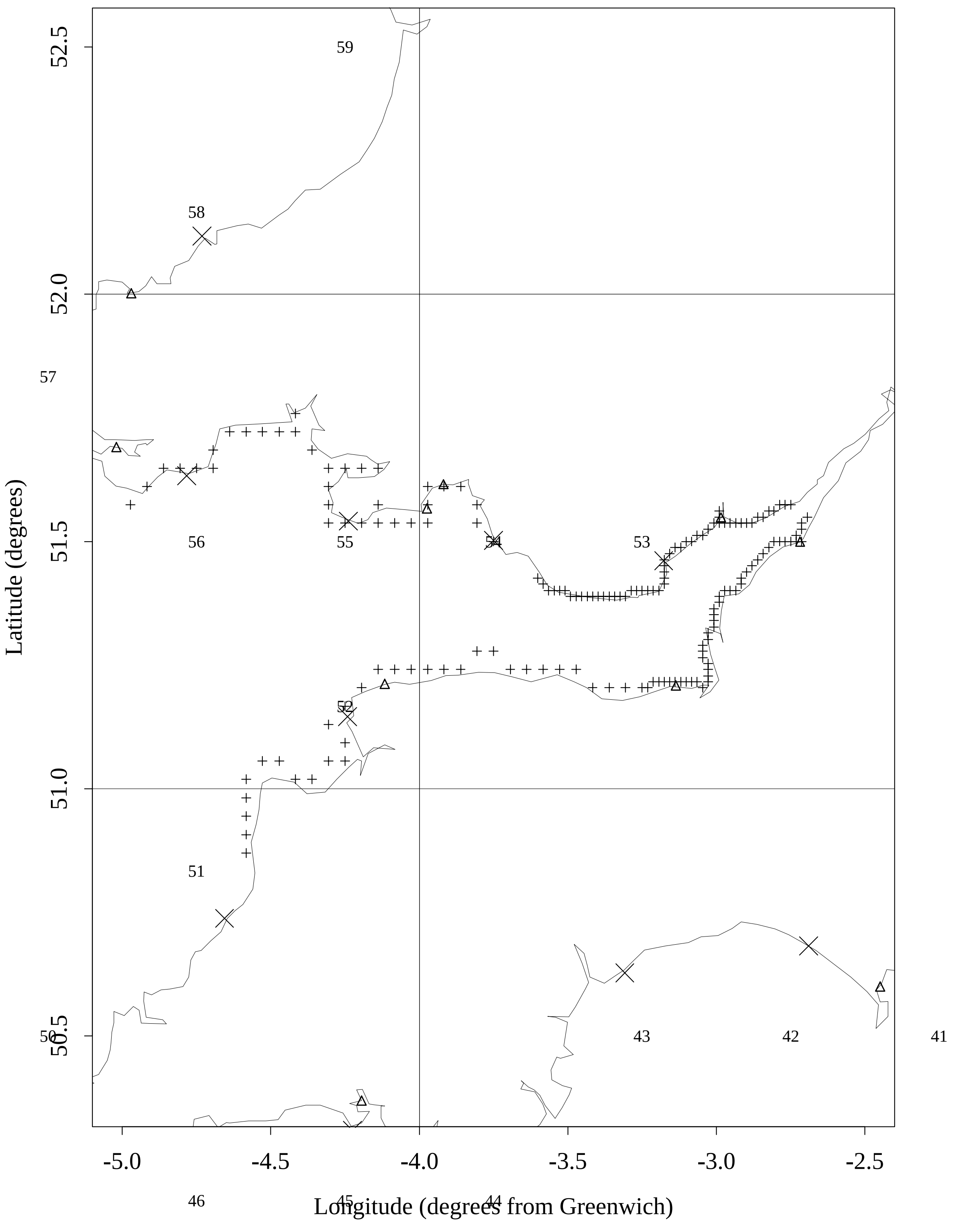

Figure 9.1: Map of the Bristol Channel and Severn estuary numerical model data. The plus symbols denote the high resolution numerical model grid locations, the numbers 42 to 59 represent the 36km grid model. The crosses denote the UK data sites.

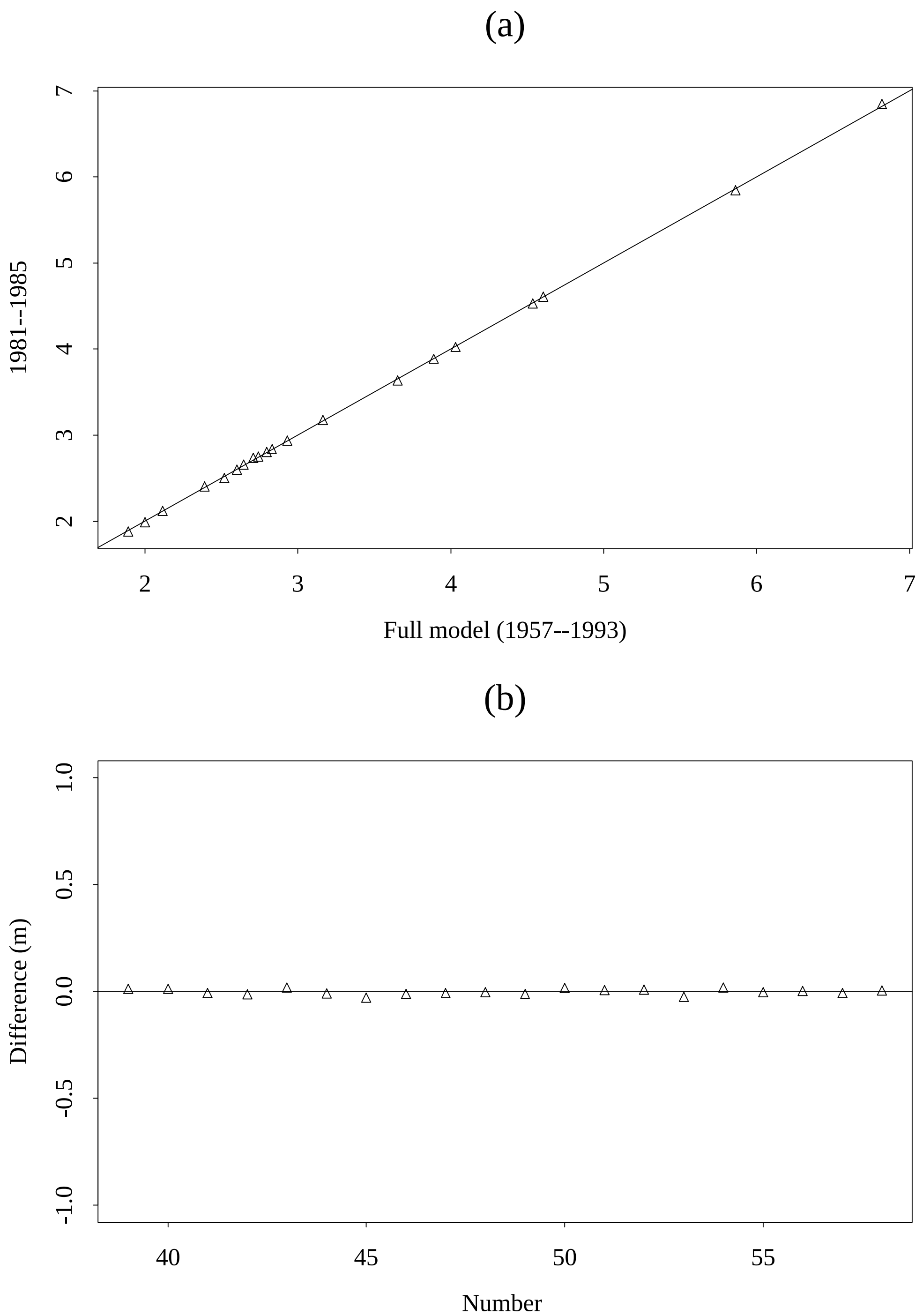

Figure 9.2: (a): estimates of the 1 year level from a selection (grid point numbers 39 to 58) of the 36km grid model points calculated using five years of data plotted against the full data. The solid line is the line $y = x$. (b): the difference in the two estimates.

Numb.	Long.	Lat.	Dist.(km)	Numb.	Long.	Lat.	Dist.(km)	Numb.	Long.	Lat.	Dist.(km)
1	-4.58	50.87	0	29	-3.42	51.20	128	58	-2.99	51.39	198
2	-4.58	50.91	5	30	-3.36	51.20	132	59	-2.97	51.40	200
3	-4.58	50.94	11	31	-3.31	51.20	136	60	-2.95	51.40	201
4	-4.58	50.98	15	32	-3.25	51.20	140	61	-2.94	51.40	203
5	-4.58	51.02	19	33	-3.23	51.20	145	62	-2.92	51.41	204
6	-4.53	51.06	23	34	-3.21	51.22	149	63	-2.92	51.43	205
7	-4.47	51.06	26	35	-3.19	51.22	155	64	-2.90	51.44	207
8	-4.42	51.02	32	36	-3.18	51.22	168	65	-2.88	51.45	209
9	-4.36	51.02	36	37	-3.16	51.22	170	66	-2.86	51.46	210
10	-4.31	51.06	40	38	-3.14	51.22	171	67	-2.84	51.48	212
11	-4.25	51.06	44	39	-3.12	51.22	173	68	-2.82	51.49	213
12	-4.25	51.09	49	40	-3.10	51.22	174	69	-2.81	51.50	215
13	-4.31	51.13	53	41	-3.08	51.22	175	70	-2.79	51.50	216
14	-4.25	51.17	58	42	-3.06	51.22	177	71	-2.77	51.50	218
15	-4.19	51.20	64	43	-3.05	51.20	178	72	-2.75	51.50	220
16	-4.14	51.24	68	44	-3.03	51.22	180	73	-2.71	51.50	221
17	-4.08	51.24	72	45	-3.03	51.23	181	74	-2.73	51.50	223
18	-4.03	51.24	75	46	-3.03	51.24	182	75	-2.73	51.51	224
19	-3.97	51.24	88	47	-3.03	51.25	184	76	-2.71	51.52	227
20	-3.92	51.24	92	48	-3.05	51.26	185	77	-2.71	51.54	228
21	-3.86	51.24	96	49	-3.05	51.28	186	78	-2.69	51.55	230
22	-3.81	51.28	99	50	-3.05	51.29	187	79	-2.75	51.57	231
23	-3.75	51.28	103	51	-3.03	51.30	189	80	-2.77	51.57	232
24	-3.69	51.24	107	52	-3.03	51.32	190	81	-2.79	51.57	233
25	-3.64	51.24	111	53	-3.01	51.33	192	82	-2.81	51.56	235
26	-3.58	51.24	117	54	-3.01	51.34	193	83	-2.82	51.56	236
27	-3.53	51.24	120	55	-3.01	51.35	194	84	-2.84	51.55	238
28	-3.47	51.24	124	56	-3.01	51.36	196	85	-2.86	51.55	240

Table 9.1: Reference table for locating a site on the distance metric for the SEM and BCM, given its latitude and longitude.

9.1.2 Data calibration

The BCM and SEM data may differ from neighbouring site data for reasons similar to those discussed in Chapter 2. However, there are two ways in which the comparisons differ. Firstly, the finer resolution of the data means that grid points can be located much closer to the data sites, and secondly, the principle source of variation in this region is in the tides. Consequently, we concentrate on comparing estimates of the one year level with estimates at the sites. In particular, Figure 9.3 shows the estimated one year level calculated using the raw numerical

Numb.	Long.	Lat.	Dist.(km)	Numb.	Long.	Lat.	Dist.(km)	Numb.	Long.	Lat.	Dist.(km)
86	-2.88	51.54	241	114	-3.29	51.40	288	140	-4.03	51.54	340
87	-2.90	51.54	243	115	-3.31	51.39	290	141	-4.08	51.54	343
88	-2.92	51.54	244	116	-3.32	51.39	291	142	-4.14	51.57	347
89	-2.94	51.54	249	117	-3.34	51.39	293	143	-4.14	51.54	351
90	-2.95	51.54	251	118	-3.36	51.39	295	144	-4.19	51.54	356
91	-2.97	51.54	252	119	-3.38	51.39	296	145	-4.25	51.54	360
92	-2.99	51.56	254	120	-3.40	51.39	298	146	-4.31	51.54	366
93	-2.99	51.55	255	121	-3.42	51.39	299	147	-4.31	51.57	370
94	-2.99	51.54	256	122	-3.44	51.39	300	148	-4.31	51.61	373
95	-3.01	51.54	259	123	-3.45	51.39	302	149	-4.14	51.65	377
96	-3.03	51.52	260	124	-3.47	51.39	303	150	-4.19	51.65	381
97	-3.05	51.51	261	125	-3.49	51.39	305	151	-4.25	51.65	385
98	-3.06	51.51	263	126	-3.51	51.40	307	152	-4.31	51.65	391
99	-3.08	51.50	264	127	-3.53	51.40	308	153	-4.36	51.68	396
100	-3.10	51.50	266	128	-3.55	51.40	309	154	-4.42	51.72	402
101	-3.12	51.49	268	129	-3.56	51.40	310	155	-4.42	51.76	407
102	-3.14	51.49	270	130	-3.58	51.41	312	156	-4.47	51.72	411
103	-3.16	51.48	272	131	-3.60	51.43	313	157	-4.53	51.72	415
104	-3.18	51.46	274	132	-3.75	51.50	314	158	-4.58	51.72	420
105	-3.18	51.45	275	133	-3.81	51.54	316	159	-4.64	51.72	424
106	-3.18	51.44	277	134	-3.81	51.57	317	160	-4.69	51.68	430
107	-3.18	51.43	278	135	-3.86	51.61	319	161	-4.69	51.65	434
108	-3.18	51.41	279	136	-3.92	51.61	322	162	-4.75	51.65	439
109	-3.19	51.40	281	137	-3.97	51.61	326	163	-4.81	51.65	443
110	-3.21	51.40	282	138	-3.97	51.57	330	164	-4.86	51.65	447
111	-3.23	51.40	284	139	-3.97	51.54	336	165	-4.92	51.61	451
112	-3.25	51.40	286	140	-4.03	51.54	340	166	-4.97	51.57	455

Table 9.2: Reference table for locating a site on the distance metric for the SEM and BCM, given its latitude and longitude.

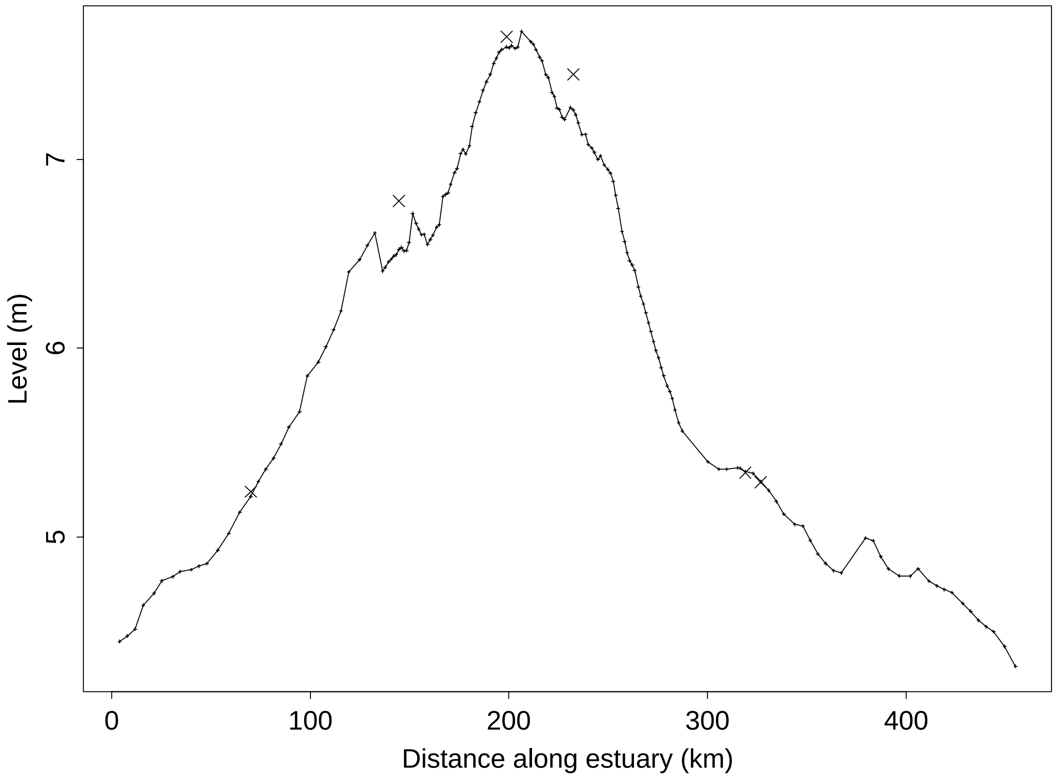

Figure 9.3: One year level estimated using the raw numerical model data combining the 4km Bristol Channel and the 1.3km Severn Estuary models plotted against coastal distance.

model data from the BCM and the SEM, plotted against distance along the estuary as defined in Tables 9.1 and 9.2. Also shown on the figure are the estimated one year levels at the sites. In general there is very close agreement between the two, although there are some significant differences. Our approach is to calibrate the numerical model for these differences in the one year level, using the same technique to that used in Chapter 7 for parameter estimate calibration. Figure 9.4 shows the adjustment calculated as a spatial smoothing of the differences between the site estimates and the estimate from the nearest model grid point.

Applying this adjustment, Figure 9.5 shows the corrected (and uncorrected) estimate of the one year level based on the BCM and SEM data. This spatial estimate is a near perfect fit to the estimates at the data sites. The estimated one year level is tabulated in Tables 9.3 and 9.4, using the SE and BC distance metric.

To emphasise the spatial gain in information from using the fine models over the coarse model of Chapters 2-8, Figure 9.5 shows the spatial estimated one year level plotted against distance for the BC and SE regions. The extent of the rough approximation made by the 36km

Dist.(km)	1 yr (m)	Dist.(km)	1 yr (m)	Dist.(km)	1 yr (m)
0	4.74	128	6.69	198	7.10
5	4.45	132	6.78	200	7.17
11	4.48	136	6.85	201	7.19
15	4.51	140	6.65	203	7.16
19	4.64	145	6.67	204	7.20
23	4.71	149	6.69	205	7.30
26	4.77	155	6.71	207	7.37
32	4.80	168	6.72	209	7.42
36	4.83	170	6.73	210	7.48
40	4.84	171	6.76	212	7.52
44	4.86	173	6.76	213	7.56
49	4.88	174	6.74	215	7.62
53	4.95	175	6.74	216	7.64
58	5.04	177	6.78	218	7.67
64	5.16	178	6.93	220	7.69
68	5.24	180	6.88	221	7.70
72	5.32	181	6.85	223	7.70
75	5.39	182	6.81	224	7.71
88	5.45	184	6.81	227	7.70
92	5.54	185	6.75	228	7.70
96	5.64	186	6.77	230	7.79
99	5.73	187	6.79	231	7.74
103	5.94	189	6.83	232	7.73
107	6.05	190	6.84	233	7.70
111	6.15	192	6.98	235	7.66
117	6.27	193	6.98	236	7.65
120	6.39	194	6.99	238	7.58
124	6.61	196	7.03	240	7.56

Table 9.3: Estimated 1 year level (to MSL) against the distance metric for the Bristol Channel and Severn Estuary.

Dist.(km)	1 yr (m)	Dist.(km)	1 yr (m)	Dist.(km)	1 yr (m)
241	7.48	288	6.55	340	5.18
243	7.47	290	6.45	343	5.12
244	7.41	291	6.40	347	5.06
249	7.40	293	6.35	351	5.05
251	7.36	295	6.30	356	4.98
252	7.35	296	6.24	360	4.90
254	7.42	298	6.18	366	4.85
255	7.41	299	6.12	370	4.82
256	7.38	300	6.07	373	4.80
259	7.34	302	6.02	377	4.99
260	7.28	303	5.96	381	4.98
261	7.29	305	5.91	385	4.89
263	7.23	307	5.85	391	4.83
264	7.22	308	5.81	396	4.79
266	7.20	309	5.77	402	4.79
268	7.16	310	5.70	407	4.83
270	7.18	312	5.63	411	4.77
272	7.13	313	5.58	415	4.74
274	7.11	314	5.40	420	4.72
275	7.09	316	5.36	424	4.71
277	7.04	317	5.36	430	4.65
278	6.97	319	5.36	434	4.61
279	6.90	322	5.34	439	4.56
281	6.77	326	5.33	443	4.52
282	6.71	330	5.29	447	4.50
284	6.65	336	5.24	451	4.42
286	6.61	340	5.18	455	4.31

Table 9.4: Estimated 1 year level (to MSL) against the distance metric for the Bristol Channel and Severn Estuary.

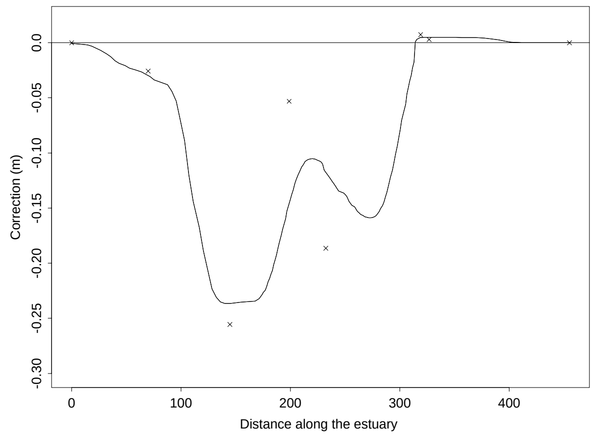

Figure 9.4: Spatial adjustment to 1 year level due to hourly data

grid model is clearly evident and differs by up to 1m from the high resolution estimate. This highlights the need for care in using results from the coarse model for complex coastal regions.

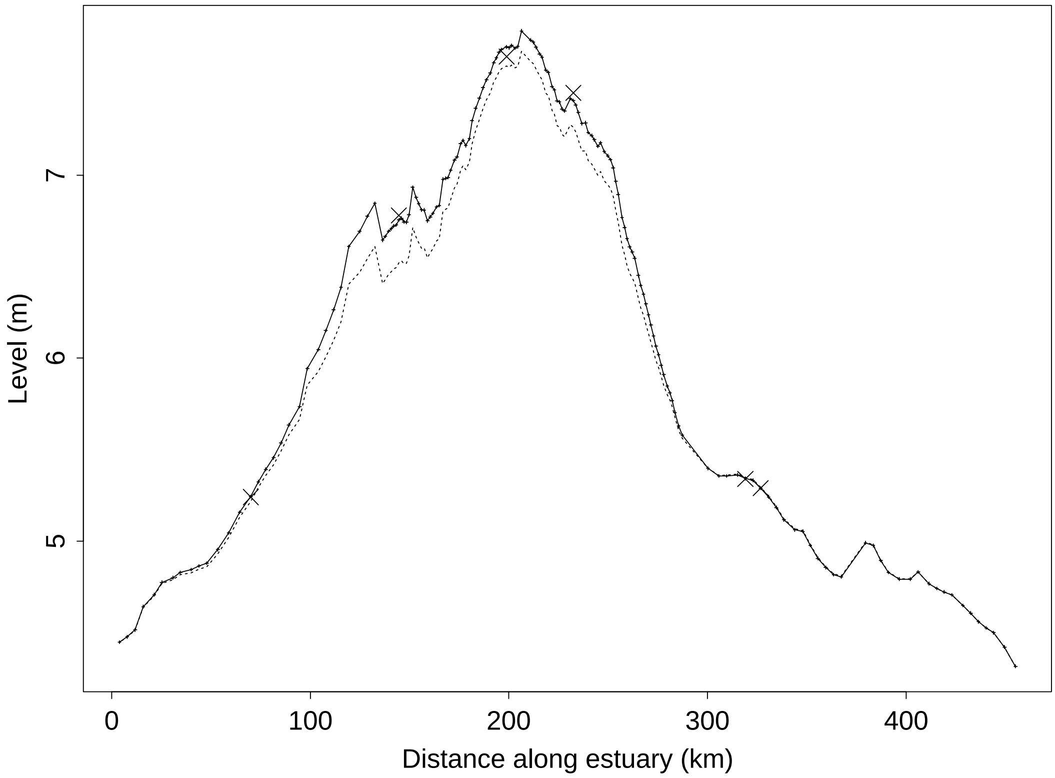

Figure 9.5: The solid line represents the one year level estimated using the numerical model data, spatially corrected using site data, plotted against coastal distance. The dashed line is the raw numerical model estimate.

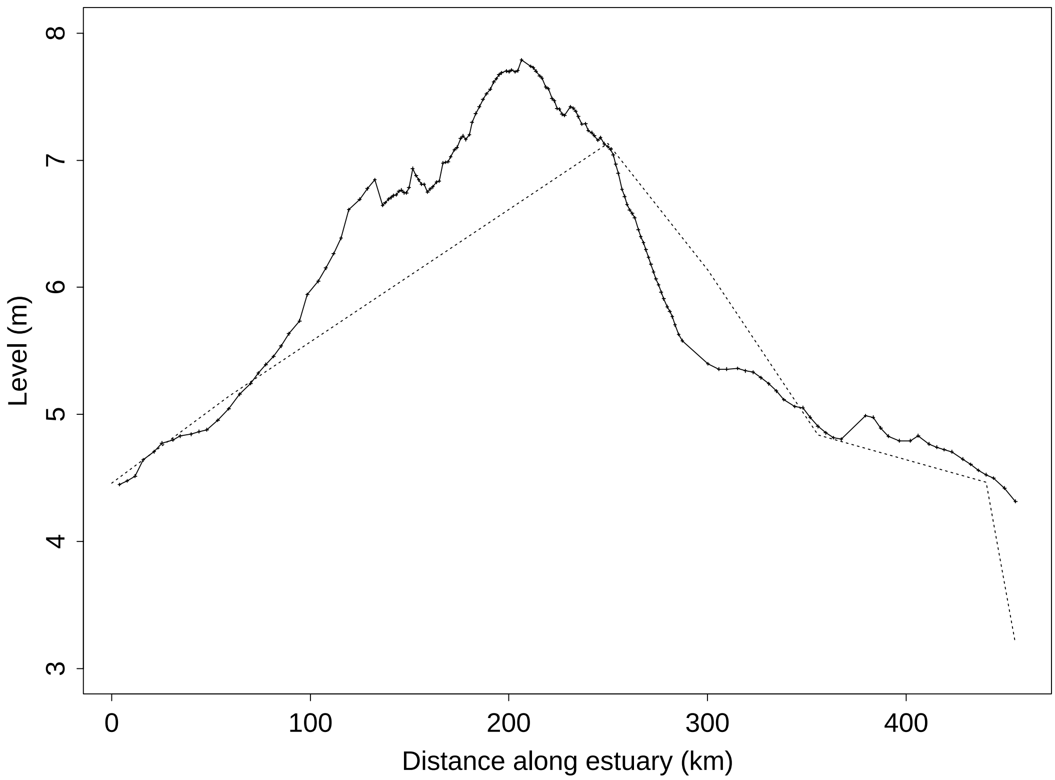

Figure 9.6: The solid line is the one year level as obtained by the spataily adjusted fine grid model and the broken line is the estimate obtained using the coarse model of Chapter 8.

9.2 Relative return level results

Tables 9.5 to 9.8 give the relative return levels for the 10 to the 10000 year return periods for the BC and SE. The tables are in the same format as Tables 8.1-8.3, and should be used in the same way as in Chapter 8. The high resolution means that the relative return levels change very slowly with distance, and interpolation to a given site is simple.

Dist (km)	10	25	50	100	250	500	1000	10000
0	0.21	0.32	0.39	0.51	0.62	0.69	0.77	1.05
5	0.21	0.32	0.39	0.51	0.62	0.69	0.77	1.05
11	0.21	0.32	0.39	0.51	0.62	0.69	0.78	1.05
15	0.21	0.32	0.40	0.51	0.62	0.69	0.78	1.05
19	0.21	0.33	0.40	0.51	0.62	0.69	0.78	1.05
23	0.21	0.33	0.40	0.51	0.63	0.69	0.78	1.06
26	0.21	0.33	0.40	0.51	0.63	0.70	0.78	1.06
32	0.21	0.33	0.40	0.52	0.63	0.70	0.79	1.06
36	0.21	0.33	0.40	0.52	0.63	0.70	0.79	1.07
40	0.21	0.33	0.40	0.52	0.63	0.70	0.79	1.07
44	0.22	0.33	0.40	0.52	0.63	0.70	0.79	1.07
49	0.22	0.33	0.40	0.52	0.63	0.70	0.79	1.07
53	0.22	0.33	0.40	0.52	0.64	0.71	0.79	1.08
58	0.22	0.33	0.40	0.52	0.64	0.71	0.80	1.08
64	0.22	0.33	0.40	0.52	0.64	0.71	0.80	1.08
68	0.22	0.33	0.40	0.53	0.64	0.71	0.80	1.09
72	0.22	0.33	0.40	0.53	0.64	0.71	0.80	1.09
75	0.22	0.33	0.41	0.53	0.64	0.72	0.81	1.09
88	0.22	0.33	0.41	0.53	0.65	0.72	0.81	1.10
92	0.22	0.33	0.41	0.53	0.65	0.72	0.81	1.10
96	0.22	0.33	0.41	0.53	0.65	0.72	0.81	1.10
99	0.22	0.34	0.41	0.53	0.65	0.72	0.82	1.11
103	0.22	0.34	0.41	0.54	0.66	0.73	0.82	1.11
107	0.22	0.34	0.42	0.54	0.66	0.73	0.83	1.12
111	0.22	0.34	0.42	0.54	0.67	0.74	0.83	1.13
117	0.22	0.34	0.42	0.55	0.67	0.74	0.84	1.14
120	0.23	0.35	0.43	0.55	0.68	0.75	0.85	1.15
124	0.23	0.35	0.43	0.56	0.68	0.76	0.85	1.16
128	0.23	0.36	0.44	0.57	0.70	0.77	0.87	1.18
132	0.24	0.36	0.45	0.58	0.71	0.78	0.88	1.20
136	0.24	0.37	0.45	0.59	0.72	0.80	0.90	1.22
140	0.25	0.38	0.46	0.60	0.74	0.81	0.92	1.24
145	0.25	0.38	0.47	0.61	0.74	0.82	0.92	1.25
149	0.25	0.39	0.47	0.61	0.75	0.83	0.93	1.27
155	0.25	0.39	0.48	0.62	0.75	0.84	0.94	1.28
168	0.25	0.39	0.48	0.62	0.76	0.84	0.95	1.28
170	0.26	0.40	0.49	0.63	0.77	0.85	0.96	1.29
171	0.26	0.40	0.49	0.63	0.77	0.86	0.96	1.30
173	0.26	0.41	0.49	0.64	0.78	0.86	0.97	1.32
174	0.26	0.41	0.50	0.64	0.79	0.87	0.98	1.33
175	0.27	0.41	0.50	0.65	0.79	0.88	0.99	1.34
177	0.27	0.42	0.51	0.66	0.80	0.89	1.00	1.35

Table 9.5: Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary.

Dist (km)	10	25	50	100	250	500	1000	10000
178	0.27	0.42	0.51	0.66	0.81	0.90	1.01	1.36
180	0.27	0.43	0.52	0.67	0.82	0.91	1.02	1.38
181	0.28	0.43	0.53	0.68	0.83	0.91	1.03	1.39
182	0.28	0.44	0.53	0.68	0.83	0.92	1.04	1.40
184	0.28	0.44	0.54	0.69	0.84	0.93	1.05	1.41
185	0.29	0.45	0.54	0.70	0.85	0.94	1.06	1.43
186	0.29	0.45	0.55	0.70	0.86	0.95	1.07	1.44
187	0.29	0.45	0.55	0.71	0.86	0.96	1.07	1.45
189	0.29	0.46	0.56	0.72	0.87	0.96	1.08	1.46
190	0.30	0.46	0.56	0.72	0.88	0.97	1.09	1.47
192	0.30	0.47	0.57	0.73	0.89	0.98	1.10	1.49
193	0.30	0.47	0.57	0.74	0.89	0.99	1.11	1.50
194	0.30	0.47	0.58	0.74	0.90	0.99	1.12	1.50
196	0.31	0.48	0.58	0.74	0.90	1.00	1.12	1.51
197	0.31	0.48	0.58	0.75	0.91	1.01	1.13	1.52
198	0.31	0.49	0.59	0.75	0.92	1.01	1.14	1.53
200	0.31	0.49	0.59	0.76	0.92	1.02	1.14	1.54
201	0.32	0.49	0.59	0.76	0.93	1.02	1.15	1.55
203	0.32	0.49	0.60	0.77	0.93	1.03	1.15	1.55
204	0.32	0.50	0.60	0.77	0.93	1.03	1.16	1.56
205	0.32	0.50	0.60	0.77	0.94	1.04	1.16	1.56
207	0.32	0.50	0.61	0.78	0.94	1.04	1.17	1.57
209	0.32	0.50	0.61	0.78	0.95	1.04	1.17	1.58
210	0.33	0.51	0.61	0.78	0.95	1.05	1.18	1.58
212	0.33	0.51	0.61	0.79	0.95	1.05	1.18	1.58
213	0.33	0.51	0.62	0.79	0.96	1.05	1.18	1.59
215	0.33	0.51	0.62	0.79	0.96	1.06	1.19	1.59
216	0.33	0.51	0.62	0.79	0.96	1.06	1.19	1.59
218	0.33	0.52	0.62	0.79	0.96	1.06	1.19	1.60
220	0.33	0.52	0.62	0.80	0.96	1.06	1.19	1.60
221	0.34	0.52	0.62	0.80	0.96	1.06	1.19	1.60
223	0.34	0.52	0.63	0.80	0.97	1.06	1.19	1.60
224	0.34	0.52	0.63	0.80	0.97	1.07	1.19	1.60
227	0.34	0.52	0.63	0.80	0.97	1.07	1.19	1.60
228	0.34	0.52	0.63	0.80	0.97	1.07	1.20	1.60
230	0.34	0.52	0.63	0.80	0.97	1.07	1.20	1.60
231	0.34	0.53	0.63	0.80	0.97	1.07	1.20	1.60
232	0.34	0.53	0.63	0.80	0.97	1.07	1.20	1.60
233	0.34	0.53	0.63	0.80	0.97	1.07	1.20	1.60
235	0.34	0.53	0.63	0.80	0.97	1.07	1.20	1.60
236	0.34	0.53	0.63	0.80	0.97	1.07	1.20	1.60

Table 9.6: Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary.

Dist (km)	10	25	50	100	250	500	1000	10000
238	0.34	0.53	0.63	0.80	0.97	1.07	1.20	1.60
240	0.35	0.53	0.63	0.80	0.97	1.07	1.20	1.60
241	0.35	0.53	0.63	0.80	0.97	1.07	1.20	1.60
243	0.35	0.53	0.63	0.80	0.97	1.07	1.19	1.60
244	0.35	0.53	0.63	0.80	0.97	1.07	1.19	1.60
249	0.35	0.53	0.63	0.80	0.97	1.07	1.19	1.60
251	0.35	0.53	0.63	0.80	0.97	1.07	1.19	1.59
252	0.35	0.53	0.63	0.80	0.97	1.07	1.19	1.59
254	0.35	0.53	0.63	0.80	0.97	1.07	1.19	1.59
255	0.35	0.53	0.64	0.80	0.97	1.06	1.19	1.59
256	0.35	0.53	0.64	0.80	0.97	1.06	1.19	1.59
259	0.35	0.53	0.64	0.80	0.97	1.06	1.19	1.59
260	0.35	0.53	0.64	0.80	0.97	1.06	1.19	1.58
261	0.35	0.53	0.64	0.80	0.97	1.06	1.19	1.58
263	0.35	0.53	0.64	0.80	0.97	1.06	1.19	1.58
264	0.35	0.53	0.64	0.80	0.96	1.06	1.18	1.58
266	0.35	0.53	0.64	0.80	0.96	1.06	1.18	1.58
268	0.35	0.53	0.64	0.80	0.96	1.06	1.18	1.57
270	0.35	0.53	0.64	0.80	0.96	1.06	1.18	1.57
272	0.35	0.53	0.64	0.80	0.96	1.06	1.18	1.57
274	0.36	0.53	0.63	0.80	0.96	1.06	1.18	1.57
275	0.36	0.53	0.63	0.80	0.96	1.05	1.18	1.57
277	0.36	0.53	0.63	0.80	0.96	1.05	1.18	1.56
278	0.36	0.53	0.63	0.80	0.96	1.05	1.18	1.56
279	0.36	0.53	0.63	0.80	0.96	1.05	1.17	1.56
281	0.36	0.53	0.63	0.80	0.96	1.05	1.17	1.56
282	0.36	0.53	0.63	0.80	0.96	1.05	1.17	1.56
284	0.36	0.53	0.63	0.80	0.96	1.05	1.17	1.55
286	0.36	0.53	0.63	0.80	0.95	1.05	1.17	1.55
287	0.36	0.53	0.63	0.80	0.95	1.05	1.17	1.55
288	0.36	0.53	0.63	0.80	0.95	1.05	1.17	1.55
290	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.54
291	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.54
293	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.54
295	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.54
296	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.54
298	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.53
299	0.36	0.53	0.63	0.79	0.95	1.04	1.16	1.53
300	0.36	0.53	0.63	0.79	0.94	1.04	1.15	1.53
302	0.36	0.53	0.63	0.79	0.94	1.03	1.15	1.53
303	0.36	0.53	0.63	0.79	0.94	1.03	1.15	1.52
305	0.36	0.53	0.63	0.79	0.94	1.03	1.15	1.52

Table 9.7: Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary.

Dist (km)	10	25	50	100	250	500	1000	10000
307	0.36	0.53	0.63	0.79	0.94	1.03	1.15	1.52
308	0.36	0.53	0.63	0.79	0.94	1.03	1.15	1.52
309	0.36	0.53	0.63	0.79	0.94	1.03	1.14	1.51
310	0.36	0.53	0.63	0.78	0.94	1.03	1.14	1.51
312	0.36	0.53	0.63	0.78	0.93	1.02	1.14	1.51
313	0.36	0.53	0.63	0.78	0.93	1.02	1.14	1.50
314	0.36	0.53	0.62	0.77	0.92	1.01	1.12	1.47
316	0.36	0.53	0.62	0.77	0.91	1.00	1.11	1.46
317	0.36	0.52	0.62	0.76	0.91	0.99	1.10	1.45
319	0.36	0.52	0.61	0.76	0.90	0.98	1.09	1.44
322	0.36	0.52	0.61	0.75	0.90	0.98	1.09	1.43
326	0.36	0.52	0.60	0.75	0.89	0.97	1.08	1.42
330	0.35	0.51	0.60	0.74	0.88	0.97	1.07	1.41
336	0.35	0.51	0.60	0.74	0.88	0.96	1.06	1.40
340	0.35	0.51	0.59	0.73	0.87	0.95	1.06	1.38
343	0.35	0.50	0.59	0.73	0.86	0.94	1.05	1.37
347	0.34	0.50	0.58	0.72	0.85	0.93	1.04	1.36
351	0.34	0.49	0.58	0.71	0.85	0.92	1.03	1.34
356	0.34	0.49	0.57	0.71	0.84	0.92	1.02	1.33
360	0.34	0.49	0.57	0.70	0.83	0.91	1.01	1.32
366	0.33	0.48	0.56	0.70	0.82	0.90	1.00	1.31
370	0.33	0.48	0.56	0.69	0.82	0.89	0.99	1.30
373	0.33	0.47	0.55	0.68	0.81	0.88	0.98	1.28
377	0.31	0.45	0.53	0.66	0.78	0.86	0.95	1.25
381	0.31	0.45	0.53	0.65	0.78	0.85	0.94	1.23
385	0.31	0.44	0.52	0.65	0.77	0.84	0.93	1.22
391	0.30	0.44	0.52	0.64	0.76	0.83	0.93	1.21
396	0.30	0.43	0.51	0.63	0.75	0.82	0.91	1.20
402	0.29	0.43	0.50	0.63	0.74	0.81	0.90	1.19
407	0.29	0.42	0.50	0.62	0.74	0.81	0.90	1.18
411	0.29	0.42	0.49	0.61	0.73	0.80	0.89	1.17
415	0.29	0.41	0.49	0.61	0.73	0.79	0.88	1.16
420	0.28	0.41	0.49	0.61	0.72	0.79	0.88	1.16
424	0.28	0.41	0.48	0.60	0.72	0.79	0.87	1.15
430	0.28	0.41	0.48	0.60	0.71	0.78	0.87	1.14
434	0.28	0.40	0.48	0.59	0.71	0.78	0.87	1.14
439	0.27	0.40	0.47	0.59	0.71	0.77	0.86	1.14
443	0.27	0.40	0.47	0.59	0.70	0.77	0.86	1.13
447	0.27	0.40	0.47	0.59	0.70	0.77	0.86	1.13
451	0.27	0.39	0.47	0.59	0.70	0.77	0.85	1.13
455	0.27	0.39	0.47	0.58	0.70	0.76	0.85	1.12

Table 9.8: Return level estimates relative to the 1 year level, in metres, for the Bristol Channel and Severn estuary.

9.3 Trend estimates in the Severn estuary

Figure 9.7 shows the spatial trend estimate for the BC and SE regions. The estimate has been obtained by smoothing the estimate obtained from the coarse model in Table 8.6. Tables 9.9 and 9.10 give the values at every distance. As with the relative return level estimates, the trend changes very slowly over this range of distances, and interpolation to a new site is simple.

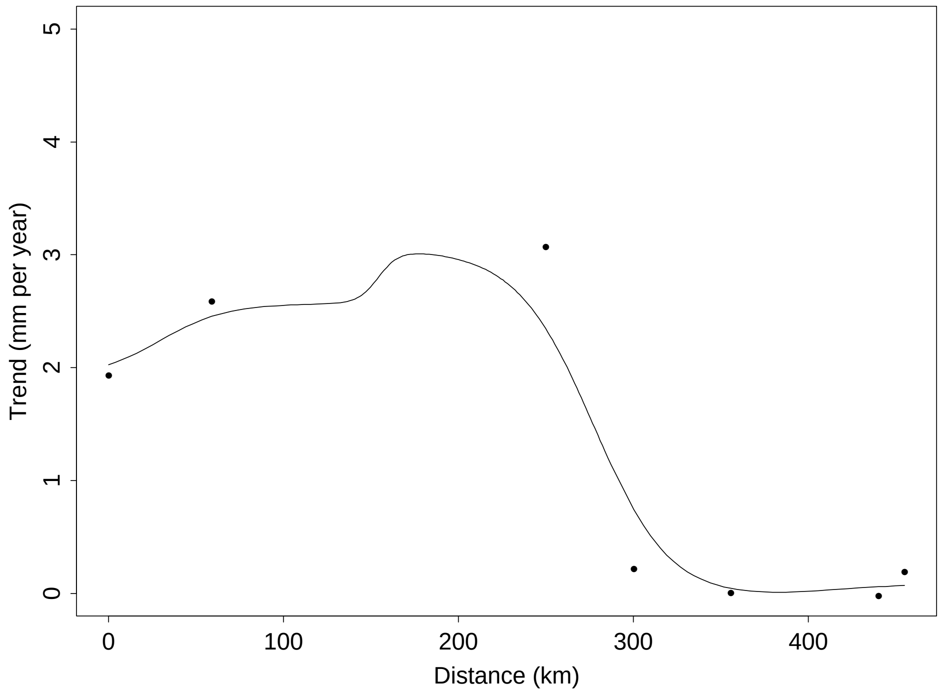

Figure 9.7: Spatial Trend estimate for the SE and BC

Dist.(km)	Trend (mm/yr)	Dist.(km)	Trend (mm/yr)	Dist.(km)	Trend (mm/yr)
0	2.03	128	2.57	198	3.01
5	2.05	132	2.57	200	3.01
11	2.07	136	2.58	201	3.01
15	2.10	140	2.59	203	3.01
19	2.13	145	2.59	204	3.01
23	2.17	149	2.60	205	3.01
26	2.20	155	2.61	207	3.00
32	2.25	168	2.62	209	3.00
36	2.28	170	2.63	210	3.00
40	2.33	171	2.64	212	2.99
44	2.36	173	2.66	213	2.99
49	2.39	174	2.67	215	2.98
53	2.42	175	2.69	216	2.98
58	2.45	177	2.71	218	2.98
64	2.48	178	2.75	220	2.97
68	2.50	180	2.78	221	2.96
72	2.51	181	2.81	223	2.96
75	2.52	182	2.83	224	2.95
88	2.53	184	2.86	227	2.94
92	2.54	185	2.89	228	2.94
96	2.54	186	2.91	230	2.93
99	2.55	187	2.93	231	2.90
103	2.55	189	2.95	232	2.89
107	2.56	190	2.97	233	2.88
111	2.56	192	2.98	235	2.87
117	2.56	193	2.99	236	2.86
120	2.56	194	2.99	238	2.84
124	2.56	196	3.00	240	2.83

Table 9.9: Estimated trend against the distance metric for the Bristol Channel and Severn Estuary.

Dist.(km)	Trend (mm/yr)	Dist.(km)	Trend (mm/yr)	Dist.(km)	Trend (mm/yr)
241	2.82	288	1.96	340	0.16
243	2.80	290	1.90	343	0.13
244	2.79	291	1.86	347	0.09
249	2.78	293	1.82	351	0.07
251	2.76	295	1.78	356	0.06
252	2.74	296	1.73	360	0.05
254	2.71	298	1.69	366	0.03
255	2.69	299	1.64	370	0.03
256	2.67	300	1.60	373	0.02
259	2.65	302	1.55	377	0.01
260	2.62	303	1.51	381	0.01
261	2.59	305	1.46	385	0.01
263	2.56	307	1.40	391	0.01
264	2.53	308	1.36	396	0.02
266	2.50	309	1.31	402	0.02
268	2.46	310	1.27	407	0.03
270	2.43	312	1.20	411	0.03
272	2.39	313	1.14	415	0.04
274	2.35	314	0.74	420	0.04
275	2.32	316	0.60	424	0.04
277	2.28	317	0.51	430	0.05
278	2.25	319	0.40	434	0.05
279	2.21	322	0.34	439	0.06
281	2.16	326	0.28	443	0.06
282	2.12	330	0.23	447	0.06
284	2.08	336	0.19	451	0.07
286	2.04	340	0.16	455	0.07

Table 9.10: Estimated trend against the distance metric for the Bristol Channel and Severn Estuary.

9.4 ODN conversion factor for the Severn estuary

Tables 9.11 and 9.12 give the spatial ODN to MSL adjustment estimate for the BC and SE regions. The estimate has been obtained by smoothing the estimate obtained from the coarse model in Chapter 8. As with the trend estimates, the adjustment factor changes very slowly over this range of distances, and interpolation to a new site is simple.

Dist.(km)	ODN to MSL (m)	Dist.(km)	ODN to MSL (m)	Dist.(km)	ODN to MSL (m)
0	0.15	128	0.15	198	0.15
5	0.15	132	0.15	200	0.15
11	0.15	136	0.15	201	0.15
15	0.15	140	0.15	203	0.15
19	0.15	145	0.15	204	0.15
23	0.15	149	0.15	205	0.15
26	0.15	155	0.15	207	0.15
32	0.15	168	0.15	209	0.15
36	0.15	170	0.15	210	0.15
40	0.15	171	0.15	212	0.15
44	0.15	173	0.15	213	0.15
49	0.15	174	0.15	215	0.15
53	0.15	175	0.15	216	0.15
58	0.15	177	0.15	218	0.15
64	0.15	178	0.15	220	0.15
68	0.15	180	0.15	221	0.15
72	0.15	181	0.15	223	0.15
75	0.15	182	0.15	224	0.15
88	0.15	184	0.15	227	0.15
92	0.15	185	0.15	228	0.15
96	0.15	186	0.15	230	0.15
99	0.15	187	0.15	231	0.15
103	0.15	189	0.15	232	0.15
107	0.15	190	0.15	233	0.15
111	0.15	192	0.15	235	0.15
117	0.15	193	0.15	236	0.15
120	0.15	194	0.15	238	0.15
124	0.15	196	0.15	240	0.15
0	0.15	197	0.15	198	0.15

Table 9.11: Estimated ODN to MSL adjustment against the distance metric for the Bristol Channel and Severn Estuary.

Dist.(km)	ODN to MSL (m)	Dist.(km)	ODN to MSL (m)	Dist.(km)	ODN to MSL (m)
241	0.15	288	0.15	340	0.14
243	0.15	290	0.15	343	0.14
244	0.15	291	0.15	347	0.14
249	0.15	293	0.15	351	0.14
251	0.15	295	0.15	356	0.14
252	0.15	296	0.15	360	0.14
254	0.15	298	0.15	366	0.14
255	0.15	299	0.15	370	0.13
256	0.15	300	0.15	373	0.13
259	0.15	302	0.15	377	0.13
260	0.15	303	0.15	381	0.13
261	0.15	305	0.15	385	0.13
263	0.15	307	0.15	391	0.13
264	0.15	308	0.14	396	0.13
266	0.15	309	0.14	402	0.13
268	0.15	310	0.14	407	0.13
270	0.15	312	0.14	411	0.13
272	0.15	313	0.14	415	0.13
274	0.15	314	0.14	420	0.13
275	0.15	316	0.14	424	0.13
277	0.15	317	0.14	430	0.13
278	0.15	319	0.14	434	0.13
279	0.15	322	0.14	439	0.13
281	0.15	326	0.14	443	0.13
282	0.15	330	0.14	447	0.13
284	0.15	336	0.14	451	0.13
286	0.15	340	0.14	455	0.13
287	0.15	288	0.15	340	0.14

Table 9.12: Estimated ODN to MSL adjustment against the distance metric for the Bristol Channel and Severn Estuary.

9.5 Comparisons of high-resolution results

Finally we compare the high resolution estimated return levels with site estimates as obtained using the AMM and CT90 methods. In particular we compare the 100 year return level at 4 sites in the BC region, Avonmouth, Newport, Cardiff and Swansea. Figure 9.8 shows the fine level estimated 100 year return level adjusted to 1990 and for ODN. Also plotted are the estimates at annual maximum data sites using the AMM and the spatial AMM as given in Coles and Tawn (1990).

The high resolution estimate agrees well with the site estimates accounting for the uncertainty of the estimates. In particular, Avonmouth and Newport have close agreement. For Cardiff and Swansea, the Coles and Tawn estimates are slightly lower than the spatial estimate obtained here. This may be due to one or more of the following reasons.

- Poor historical annual maximum data at these sites.
- Poor representation of tide-surge interaction in the high resolution numerical model data.
- Errors in either the spatial model or the spatial ODN correction estimate.

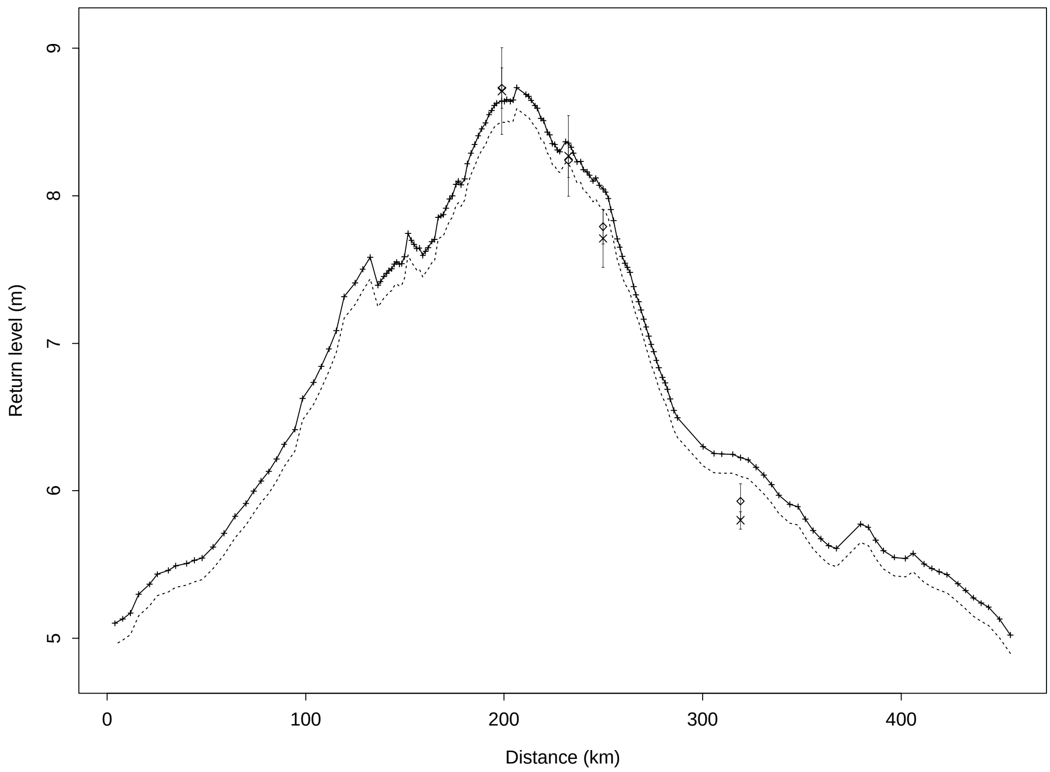

Figure 9.8: The solid line is the 100 year return level as obtained by the spatialy adjusted fine grid model adjusted to ODN. The dashed line is the estimate to MSL datum. The diamonds are the Coles and Tawn spatial estimates, and the crosses are the AMM estimates, both to ODN.

Chapter 10

Design levels and encounter risk

In presenting results, we have concentrated throughout this report, and in the previous reports DT1 and DT2, on the estimation of return levels for a specific year, 1990. All results have been presented to address the question "What is the n year return level at a given distance around the coastline?" Two important aspects in the strategic management of coastal flood defences, in addition to the design height for proposed new sea-walls, are (i) the protection offered by sea defences once they are in place, and (ii) the assessment of suitable levels for structures designed to last a number of years. The purpose of this chapter is to present the return level information of the previous chapters in a format which enables the assessment of these two aspects, namely the future protection given a specified design height and the design height for structures which are to last a specified time period.

10.1 Future protection of existing designs

Consider the situation where a sea wall has been designed to the 100 year level as specified in this report (without adjustment for trends). This level corresponds to the 100 year level at the site, for 1990. The question we consider is how much protection, in terms of the return period in a future year, is given by this design height. Clearly this depends on the trend at the site: sites with large positive trends will tend to have relatively less protection in future years than those with small or negative trends. However, the trend is not the only feature that affects the future protection. The point is illustrated in Figure 10.1 which shows port diagrams for two hypothetical sites with different shape parameter values and for different years, 1990 and 2015 based on the same trend at each location. For coastal defences designed to the 100 year level in 1990 in each case, i.e. design heights of 3.3 and 3.65m for the 0.3 and 0.0 GEV shape parameters respectively, the protection given in 30 years time has decreased from the 100 year level to (approximately) the 3 and 12 year return levels respectively. Thus the trend is only part of the reason for differing future protections; the form of the extreme tail of the sea-level

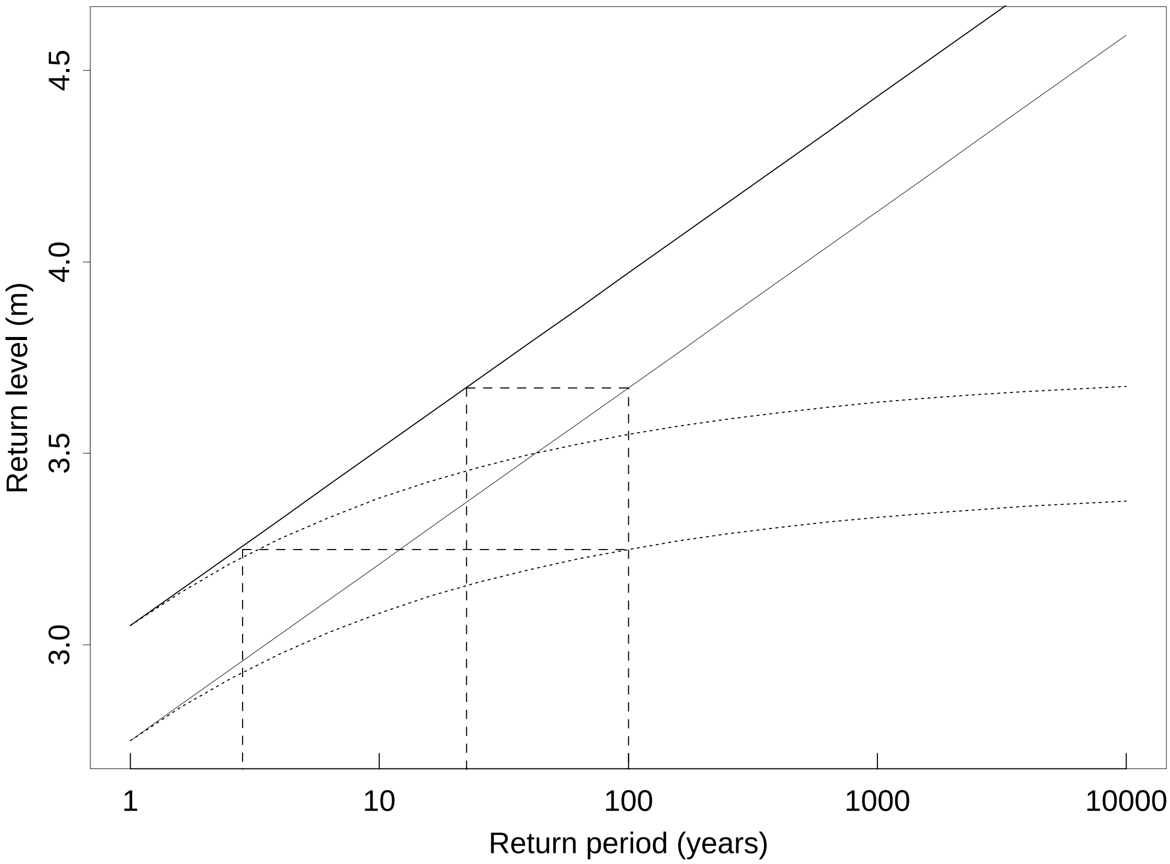

Figure 10.1: Example of different future protection. The broken port diagram lines are for 1990 and 2020 for a site with shape parameter 0.3 and trend of 1mm per year. The solid port diagram curves are for a shape parameter of 0.0, with the same trend.

distribution plays a major role also.

We now give results for the future protection for the whole coastline. Figures 10.2-10.7 show the protection 1, 5, 10, 25, 50, and 100 years ahead which would be attained from designing to the current 100 year return level at each point around the coastline. Concentrating on Figure 10.5, corresponding to 25 years ahead, we note that in general the protection is around the 70-80 year return level. However, there are exceptions, which include eastern Scotland, where there is noticeably less protection. Some areas have very little reduced protection due to either small trends or long tails of the extreme value distribution.

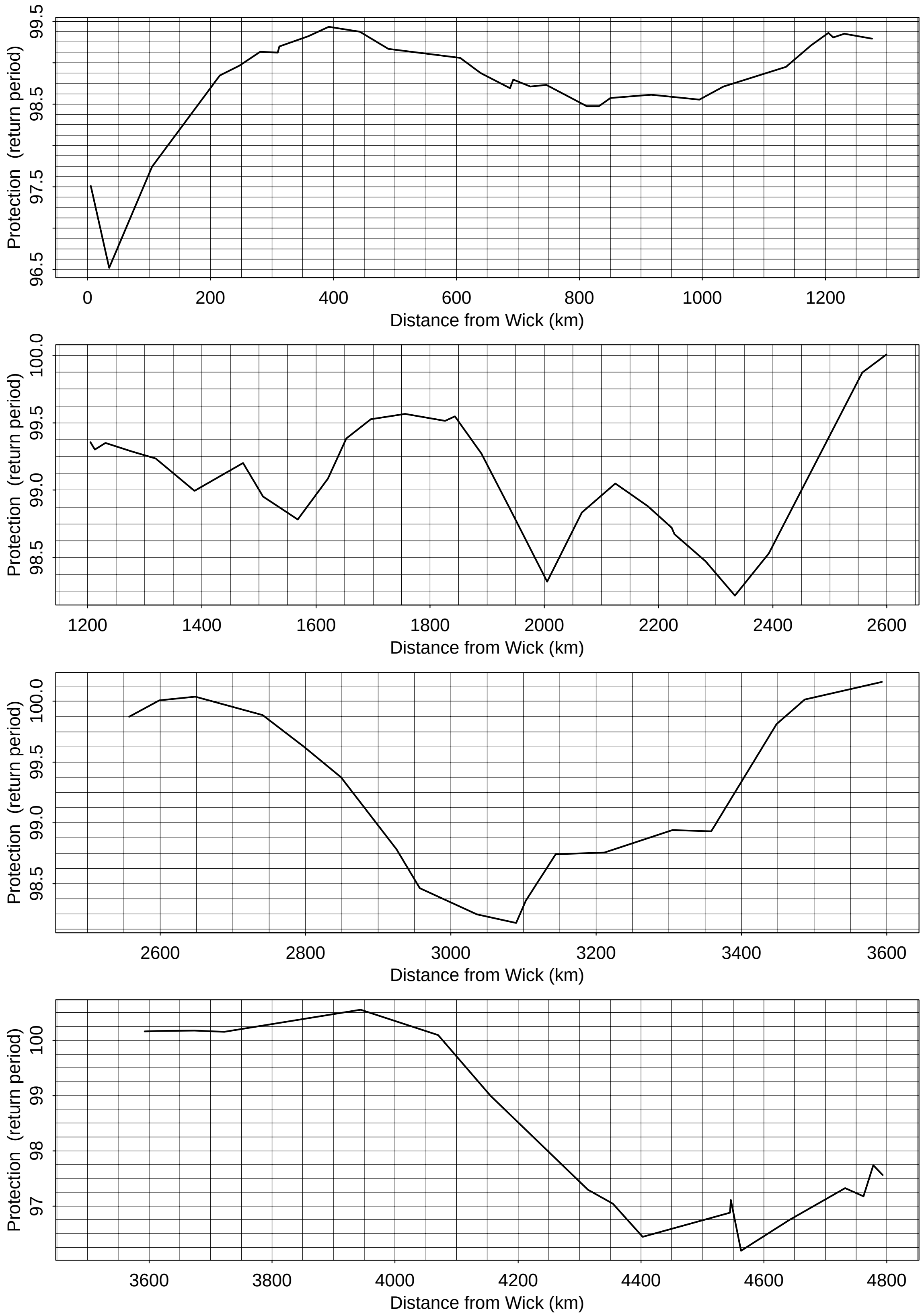

Figure 10.2: Protection given by designing to the 100 year return level in 1990, for a design in 1 years time.

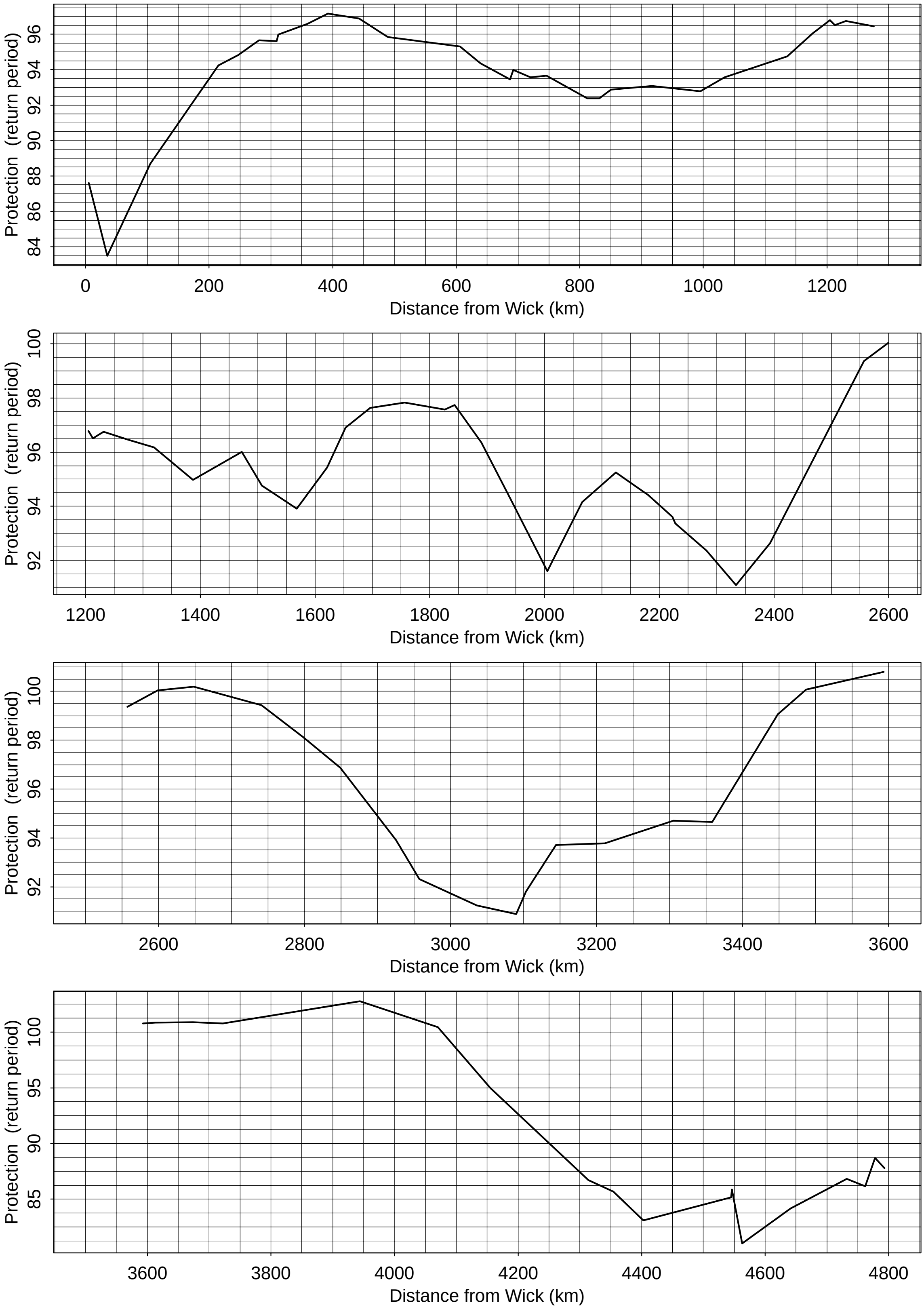

Figure 10.3: Protection given by designing to the 100 year return level in 1990, for a design in 5 years time.

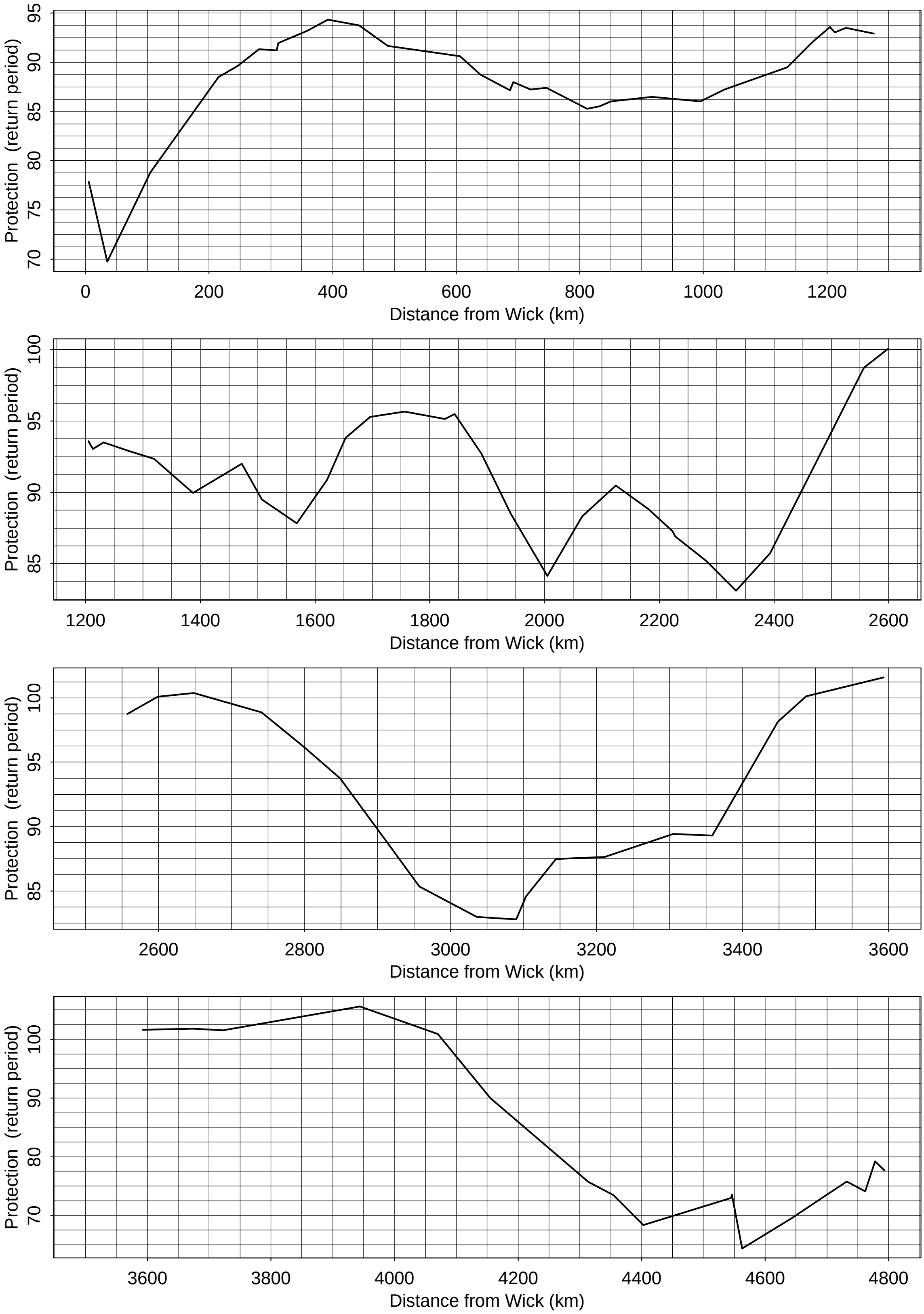

Figure 10.4: Protection given by designing to the 100 year return level in 1990, for a design in 10 years time.

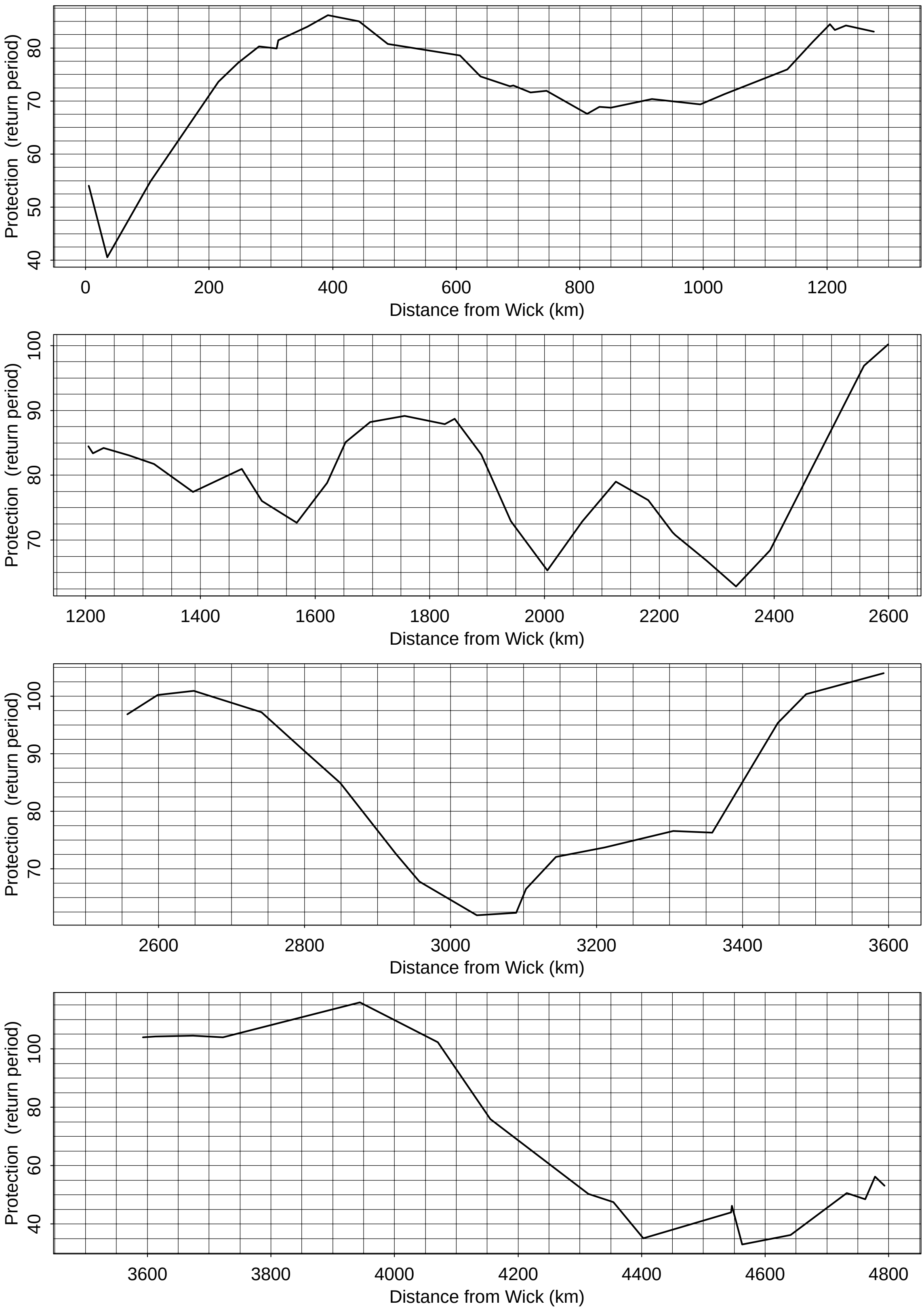

Figure 10.5: Protection given by designing to the 100 year return level in 1990, for a design in 25 years time.

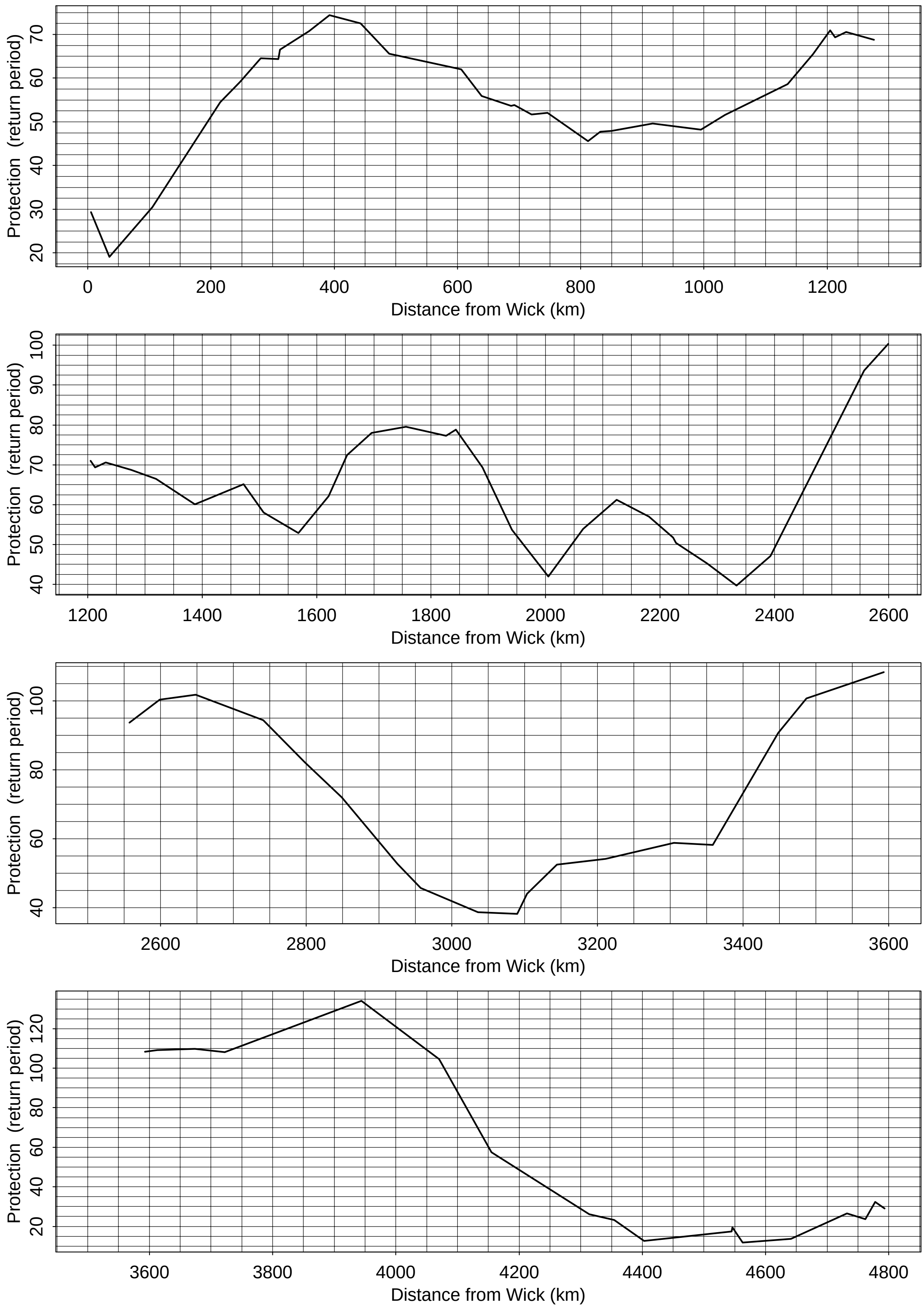

Figure 10.6: Protection given by designing to the 100 year return level in 1990, for a design in 50 years time.

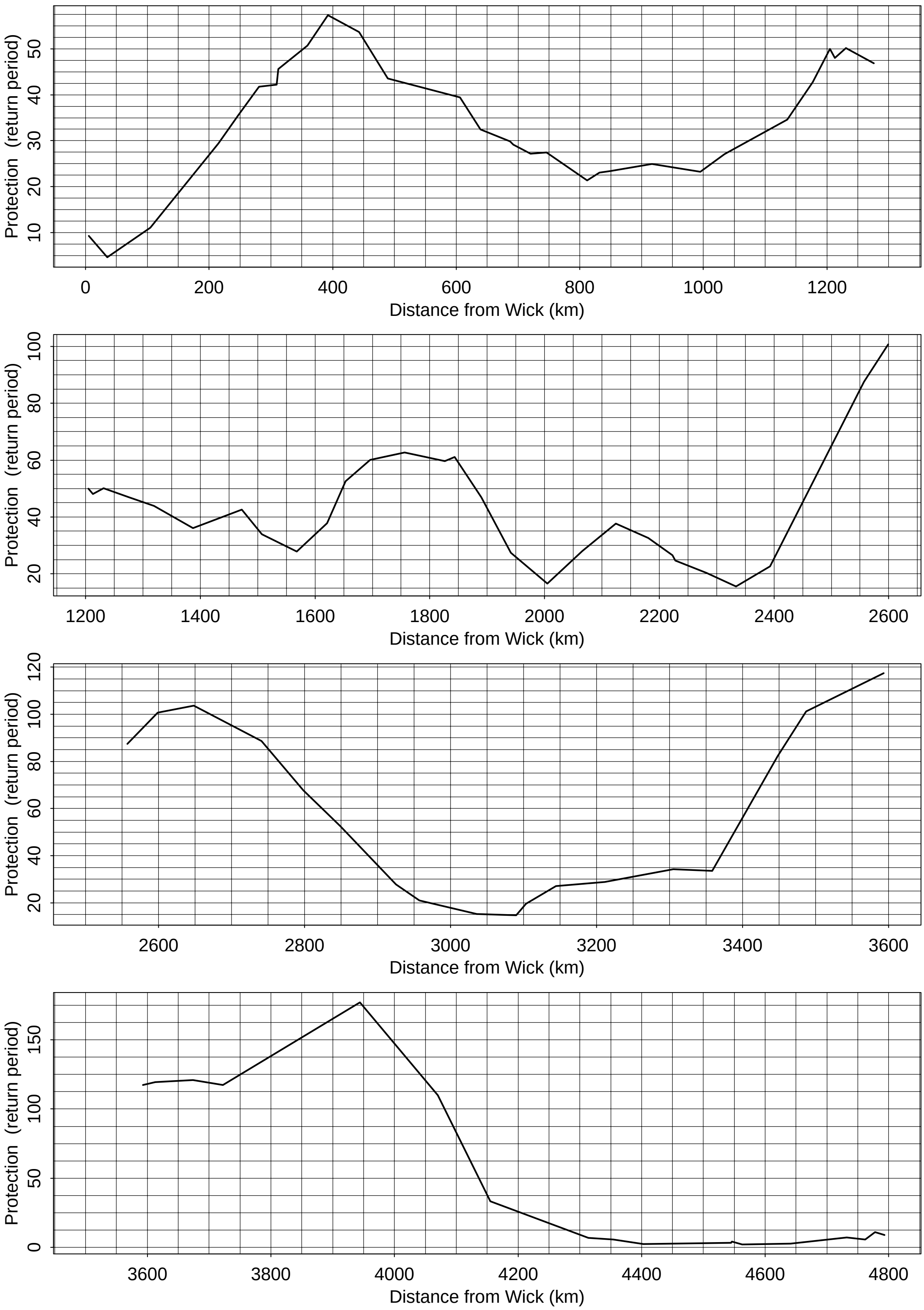

Figure 10.7: Protection given by designing to the 100 year return level in 1990, for a design in 100 years time.

10.2 Risk and long-term design

We now present results which give protection levels over various spans corresponding to the lifetime of a structure. First we summarise the definitions of return levels, return periods, and design levels.

10.2.1 Definitions of design level

The return level and return period have been used for summarising design level information throughout this and previous reports DT1 and DT2. Although, together with trend information, these variables contain all the required information for design height calculation, they are suited mainly for assessing risk for independent and identically distributed processes. Before discussing more appropriate measures, recall the motivation for and definition of return levels and return periods.

For independent and identically distributed random variables $R_1, R_2, \ldots$, suppose the common distribution function is G_R and that failure occurs at time i if $R_i > w$. Then if T_W is the waiting time to the first failure we have

$$\begin{aligned}
\Pr\{T_W = i\} &= \Pr\{\text{first failure is at time } i\} \\
&= \Pr\{R_1 \le w, R_2 \le w, \ldots, R_{i-1} \le w, R_i > w\} \\
&= \Pr\{R_1 \le w\} \Pr\{R_2 \le w\} \ldots \Pr\{R_{i-1} \le w\} \Pr\{R_i > w\} \\
&= G_R(w) \ldots G_R(w)[1 - G_R(w)] \\
&= [G_R(w)]^{i-1}[1 - G_R(w)] \\
&= \theta_w^{i-1}(1 - \theta_w), \quad \text{for} \quad i = 1, 2, \ldots
\end{aligned}$$

letting $\theta_w = G_R(w)$, so $1 - \theta_w$ is the probability of failure. This is a geometric distribution, and

$$\begin{aligned}
E(T_W) &= \sum_{i=1}^{\infty} i \Pr\{T_W = i\} \\
&= \sum_{i=1}^{\infty} i \theta_w^{i-1}(1 - \theta_w) \\
&= (1 - \theta_w)^{-1}.
\end{aligned}$$

Since the process is independent this is also the expected waiting time between failures. So the expected waiting time between failures is the reciprocal of the probability of a failure.

Definition of the return period and the return level.

The **return period** for an event corresponding to the level w, is the expected waiting time between events which exceed w. Thus the return period is $[1 - G_R(w)]^{-1}$, with time units those of the $\{R_i\}$ process. Accordingly, if w_m is a level such that $[1 - G_R(w_m)]^{-1} = m$ then we term w_m the m observation **return level**.

If R_i denotes the annual maximum sea-level in year i, then the return period of annual maximum exceedances of the level w is $[1 - G_R(w)]^{-1}$ years. Exceedances of the level w can occur more frequently than once a year, for example two or more events in a year may exceed this level, so the expected waiting time between exceedances is less than $[1 - G_R(w)]^{-1}$ years, however it can be shown that the level w has a return period of $[-\log G_R(w)]^{-1}$ years. These formulae for the return period are equivalent for long return periods, that is where $G_R(w)$ is close to one, as

$$[-\log G_R(w)]^{-1} = \{-\log[1 - (1 - G_R(w))]\}^{-1} \approx [1 - G_R(w)]^{-1}$$

but differ significantly for return periods of less than 15 years. The return period is given by

$$[-\log G_R(w)]^{-1} \qquad (10.2.1)$$

for level w. If $G_R(z(p)) = 1 - p$ then the return level $z(p)$ has return period $[-\log(1 - p)]^{-1}$ years.

Now consider how these definitions link with possible design criteria. These are

- **Definition 1**

  The height of the sea wall should be such that the probability of failure in year i is a small, pre-specified value, p.

  This level, termed the **p design level for year i**, and denoted by $z_i(p)$, satisfies

  $$\Pr\{Z_i > z_i(p)\} = 1 - G_i\{z_i(p)\} = p, \qquad (10.2.2)$$

  i.e. $z_i(p) = G_i^{-1}(1 - p)$.

  Unlike the return level this design level concept applies to processes with trends as well as stationary sequences. To clarify the connections between the concepts first consider a sea-level process without trends, in which case $G_i = G$ for all years. Then,

  $$z_i(p) = G_i^{-1}(1 - p) = G^{-1}(1 - p) = z(p)$$

  for all years and probabilities so that in this case the design level is the $[-\log(1 - p)]^{-1}$ year return level, $z(p)$. This is a suitable choice for the sea-wall, i.e. $w = z(p)$.
  If there is a linear trend in sea-levels, i.e.

  $$Z_i = \beta(i - i_0) + Z_i^*$$

  where Z_i^* is an independent and identically distributed random variable with distribution function G, i, i_0 are the year and a base year respectively and β is a linear trend parameter, then

  $$z_i(p) = G_i^{-1}(1 - p) = \beta(i - i_0) + G^{-1}(1 - p) = \beta(i - i_0) + z(p)$$

  where $z(p)$ is the $[-\log(1 - p)]^{-1}$ year return level of the Z^* variable. Thus the p design level in year i varies with the trend, and in the year corresponding to the base year the p design level is the $[-\log(1 - p)]^{-1}$ year return level of Z^*.

- **Definition 2**

  To take the height of the wall to be such that over the required lifetime of the structure, from year j_1 to year j_2, the probability of failure in any one year is less than p.

  Again consider the cases of trend and no trend separately. If there is no trend then the optimal design is such that the probability of failure in each year is p, so $w = z(p)$, with $z(p)$ the $[-\log(1-p)]^{-1}$ year return level. When there is a trend, with $\beta > 0$, then the largest probability of failure occurs in year j_2, so $w = z_{j_2}(p)$ is a suitable level, i.e. the p design level for year j_2. Similarly, if $\beta < 0$ then $w = z_{j_1}(p)$ is suitable.

- **Definition 3**

  The sea-wall height is to be designed such that the probability of failure over the entire lifetime of the structure, from year j_1 to year j_2, is equal to p.

  Alcock (1984) terms this the encounter risk. In the case of no trend, w must satisfy

  $$[G(w)]^{j_2-j_1} = 1-p \quad \text{so} \quad w = G^{-1}[(1-p)^{1/(j_2-j_1)}].$$

  More generally when a trend is present w must satisfy

  $$\prod_{i=j_1}^{j_2} G_i(w) = 1-p,$$

  and here w needs to be evaluated by numerical solution.

10.2.2 Encounter Risk

The most relevant definition for practical design is the encounter risk design level , i.e. Definition 3. We give results for this definition for the entire coastline. Figures 10.8–10.10 and 10.11–10.13 show the design level for a 25 year and 50 year lifetime respectively, and for lifetime failure probabilities of 0.01, 0.1, and $\exp(-1) = 0.37$. The level corresponding to a lifetime failure probability of $\exp(-1) = 0.37$ is sometimes a useful criterion. In the stationary case this corresponds to the probability of failure over a T year lifetime when the design is set as the T year return level for each single year (when T is large).

For an encounter risk of 0.99 over a 25 year structure lifetime, or equivalently, a lifetime failure probability of 1%, Figure 10.8 gives the design height, in terms of the return period design required in 1990, around the coastline. For most of the coastline, the return period required is between 2500 and 3000 years. Higher return periods are required around the Severn estuary, and on the northern Scottish coastline. The spatial pattern is similar for other encounter risks and for other structure lifetimes.

Figures 10.8–10.10 and 10.11–10.13 can be used directly to obtain a design level for a given lifetime and failure probability as follows.

1. Decide on the structure lifetime, 25 or 50 years.

2. Decide on the acceptable encounter risk over the structure lifetime, i.e. a failure probability of 0.01, 0.1, or 0.37.

3. Calculate the latitude-longitude and corresponding distance of the structure location, using Table 4.1 and 4.2.

4. Locate the relevant figure, and read off the 1990 return period for this design.

5. Use the procedure in Section 8.5 to calculate the design height (for 1990) corresponding to this return period, and DO NOT adjust for trends, for future years, as this has already been done in the above procedure.

6. This is the design height corresponding to the required encounter risk over the structure lifetime.

10.2.3 Worked example

We require the design height of a sea-wall at North Shields which is to last 25 years, and which will have probability of less than 0.1 of flooding over this lifetime of 25 years.

1. The structure lifetime is 25 years.

2. The lifetime failure probability over the structure lifetime is 0.1.

3. The latitude-longitude and corresponding distance is (55.01,-1.46) and 723km, from Section 8.3.

4. The relevant figure, for 25 year lifetime is Figure 10.9. The 1990 return period for this distance required to give this encounter risk is then 280 years.

5. Following the procedure in Section 8.5, we get that the 280 year return level is approximately (0.86+2.94)=3.80m (to MSL datum).

6. Thus the design height corresponding to the encounter risk over the structure lifetime of 25 years is 3.80m (to MSL datum).

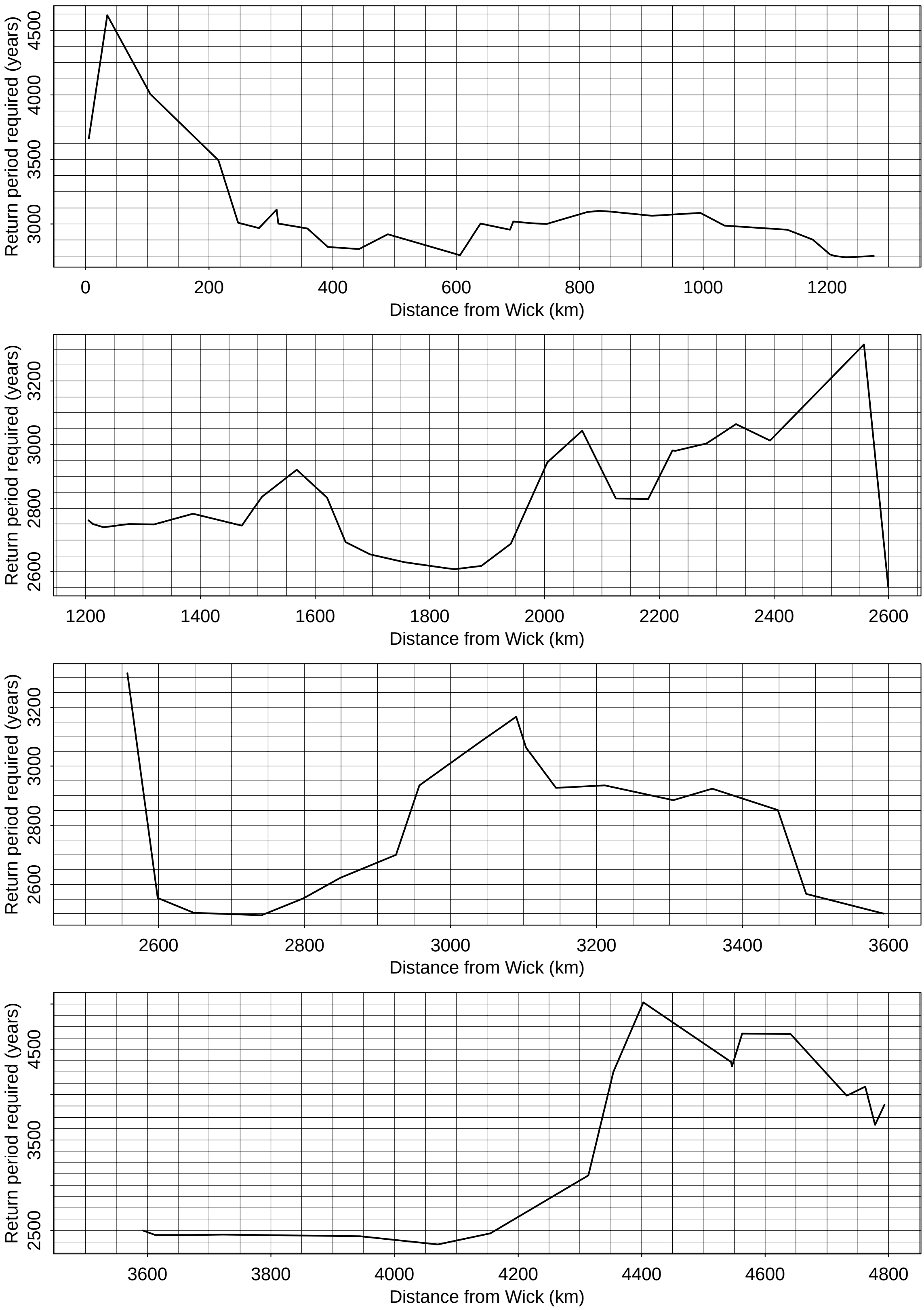

Figure 10.8: Design level for an encounter risk of 0.99, and a lifetime of 25 years plotted against distance.

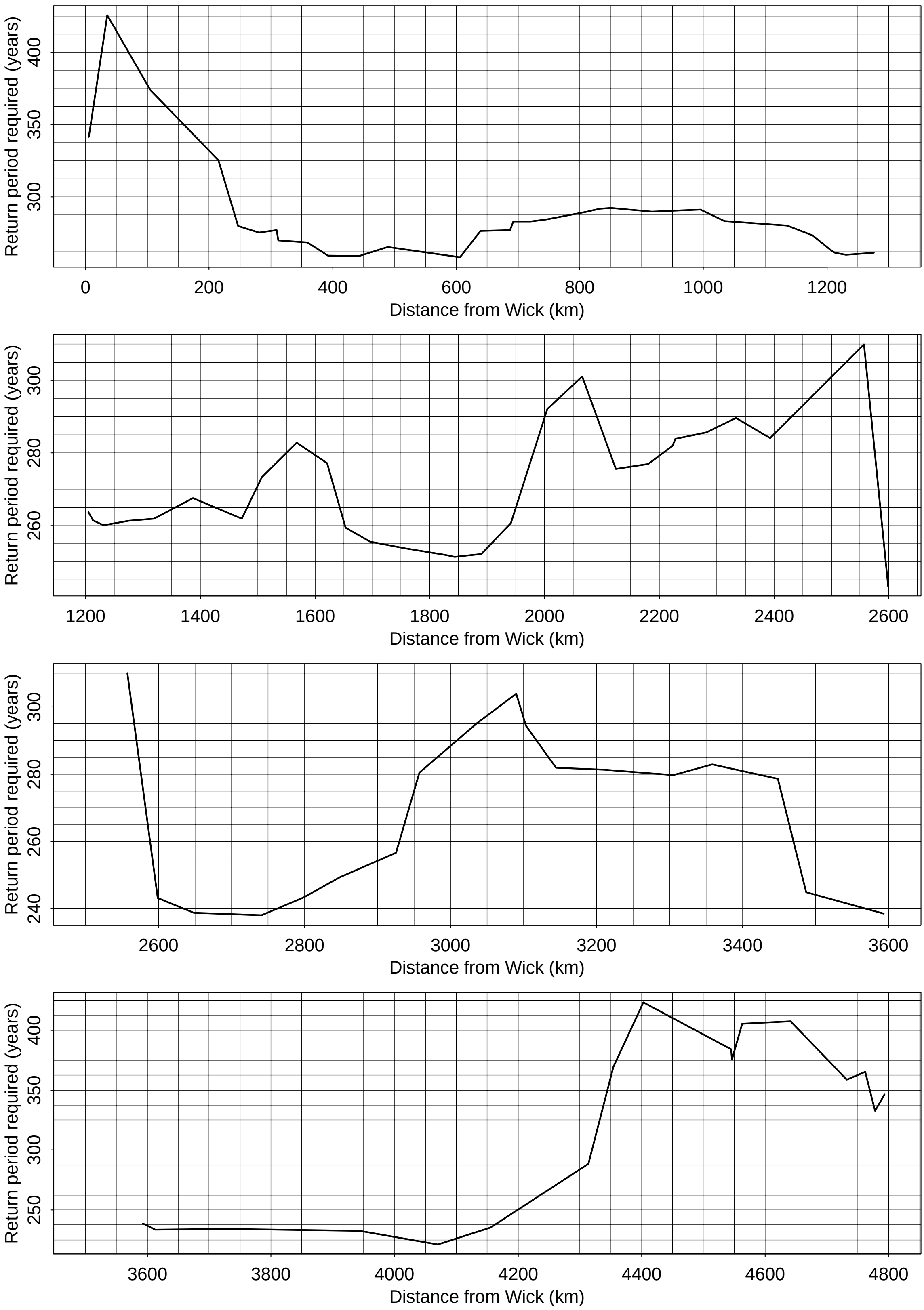

Figure 10.9: Design level for an encounter risk of 0.9, and a lifetime of 25 years plotted against distance.

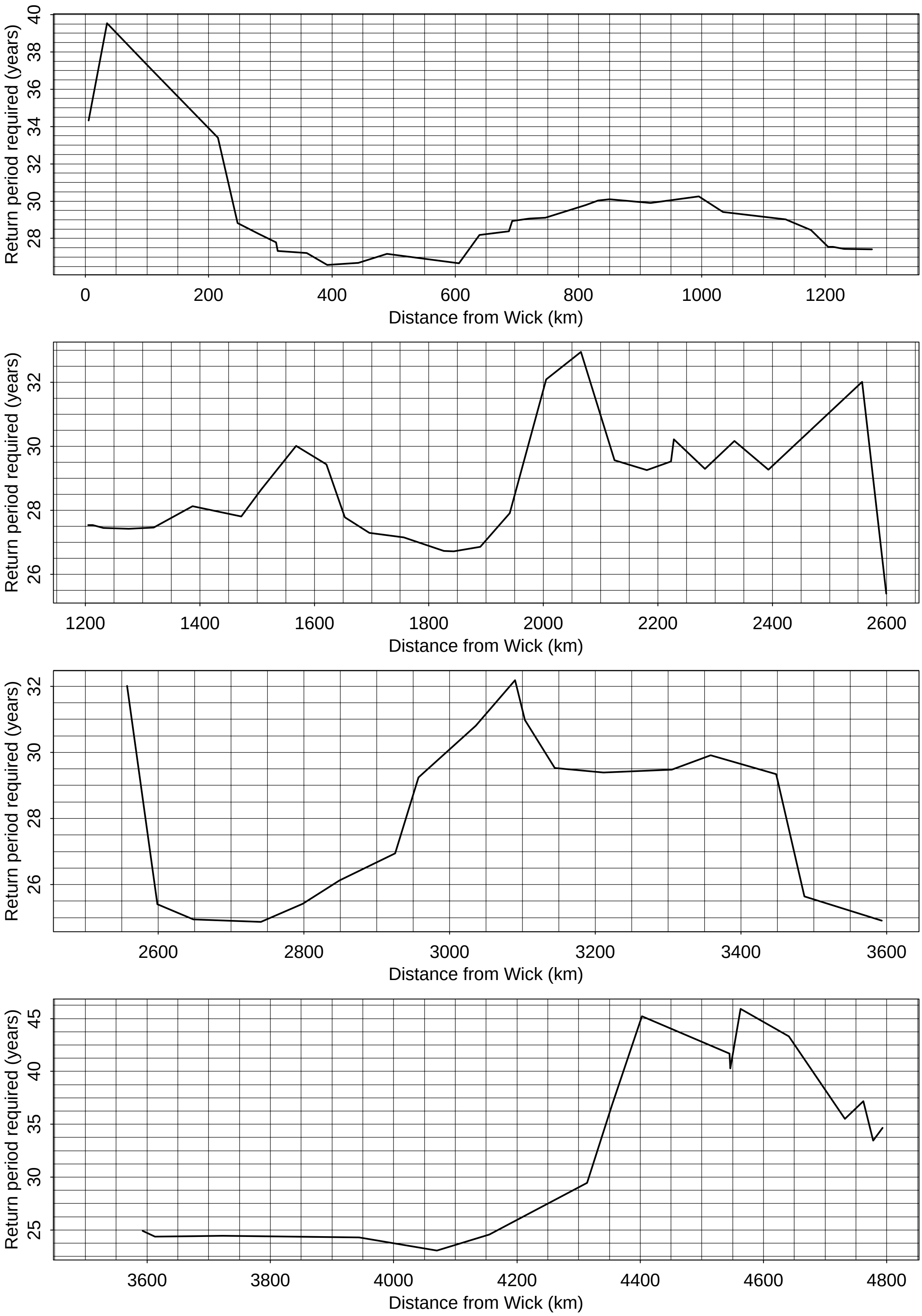

Figure 10.10: Design level for an encounter risk of 0.37, and a lifetime of 25 years plotted against distance.

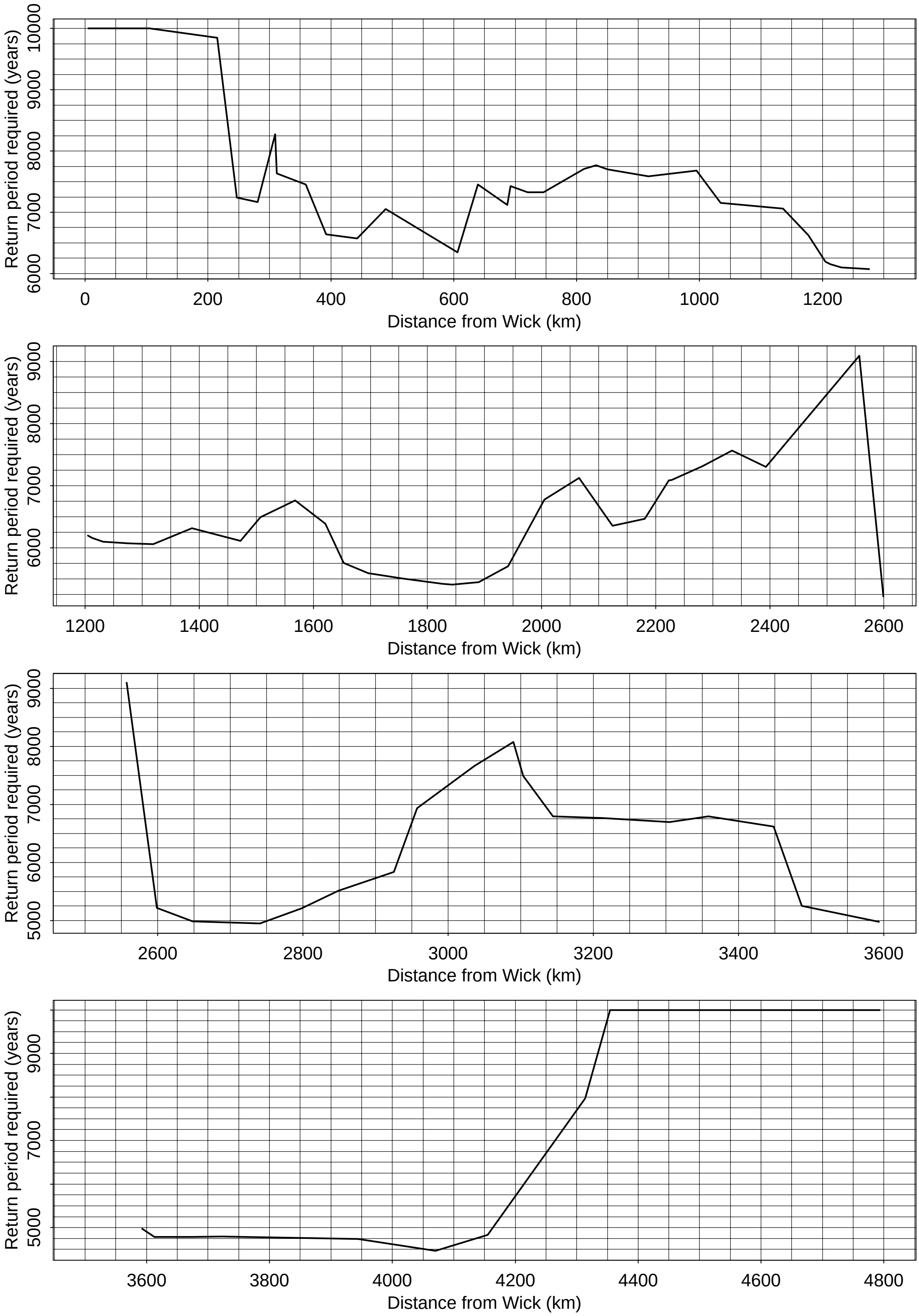

Figure 10.11: Design level for an encounter risk of 0.99, and a lifetime of 50 years plotted against distance.

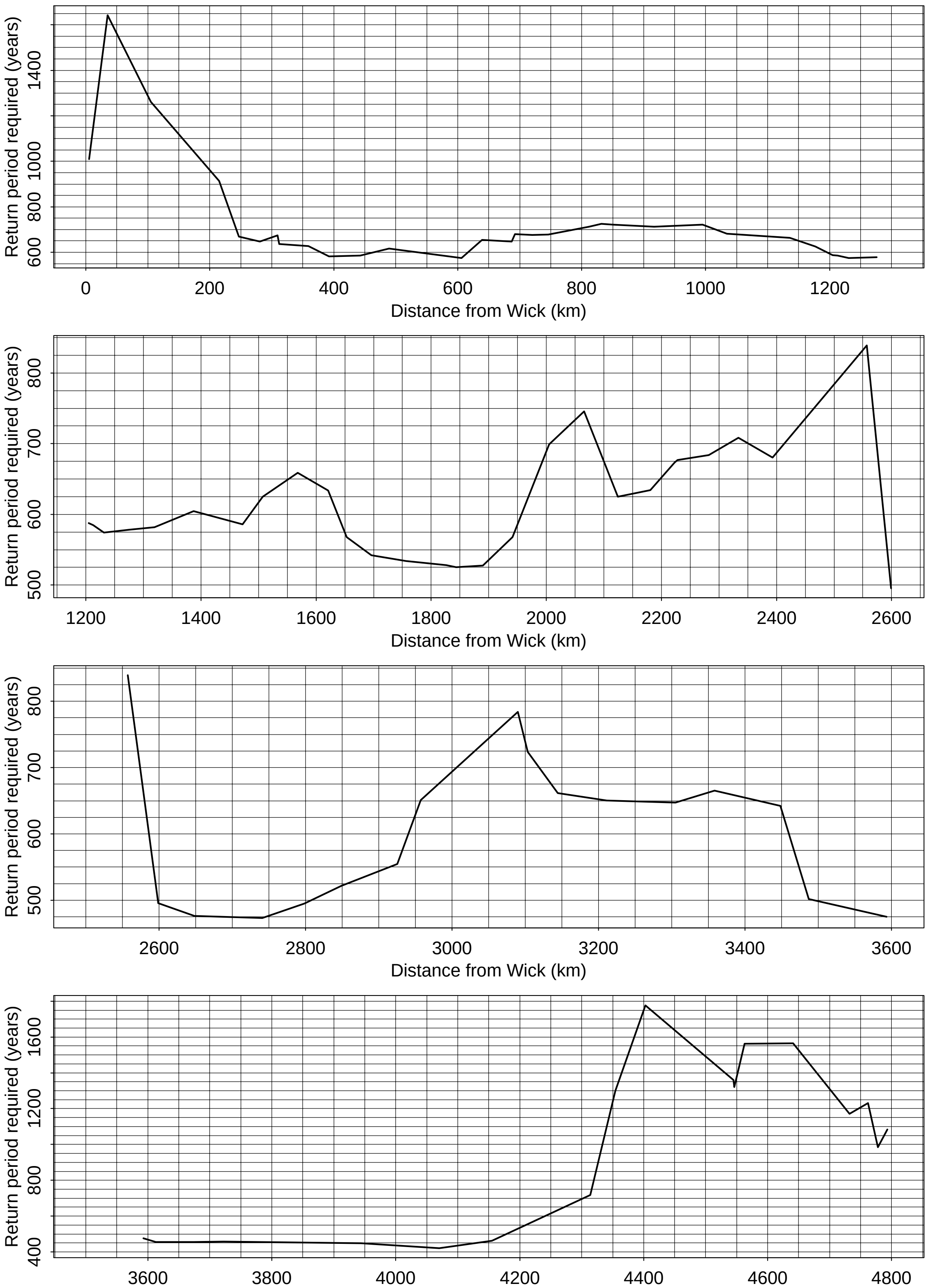

Figure 10.12: Design level for an encounter risk of 0.9, and a lifetime of 50 years plotted against distance.

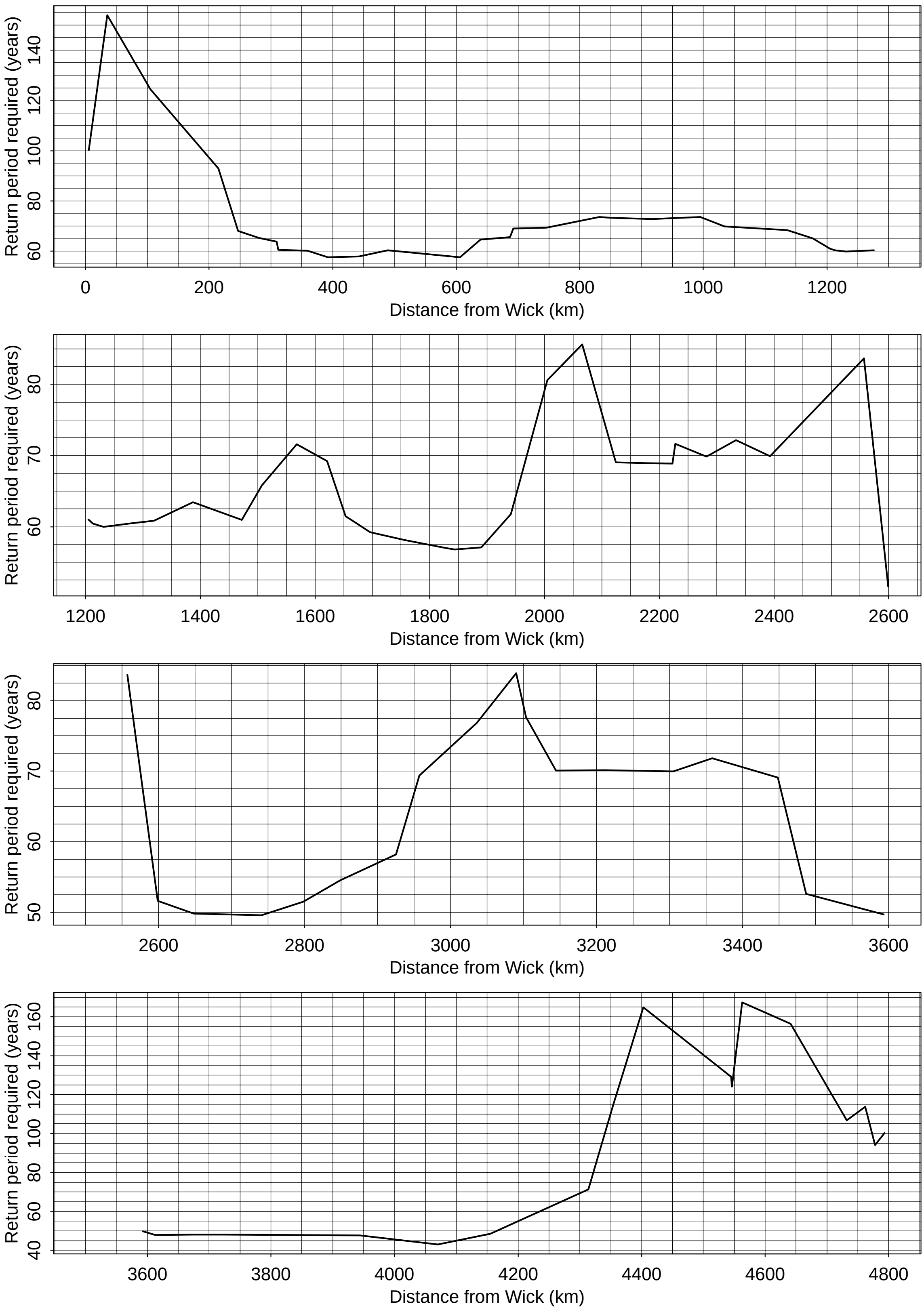

Figure 10.13: Design level for an encounter risk of 0.37, and a lifetime of 50 years plotted against distance.

Chapter 11

Acknowledgements

We thank the Ministry of Agriculture Fisheries and Food for funding this work. We have found considerable support from colleagues and POL staff. In particular at POL, we thank Ian Vassie who made a large contribution in the development of the POL tidal interpolation software, and provided much helpful and highly appreciated advice for other aspects of the work. We also thank Lisa Carlin, Roger Flather, and Joyce Tranter for providing the numerical model data and for helpful discussions and David Blackman for supplying various data and clarifying datum problems.

Chapter 12

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Chapter 13

Appendix

Site			l year return level			
Number	lat	long	l=10	l=25	l=50	l=100
1	-3.08	58.43	2.24	2.34	2.39	2.46
2	-3.20	58.32	2.24	2.34	2.39	2.46
3	-3.47	58.21	2.32	2.42	2.46	2.54
4	-3.72	58.08	2.38	2.48	2.53	2.60
5	-3.98	57.97	2.47	2.57	2.62	2.69
6	-4.27	57.87	2.51	2.61	2.65	2.73
7	-3.94	57.84	2.53	2.63	2.68	2.75
8	-4.16	57.69	2.53	2.63	2.68	2.75
9	-4.43	57.58	2.62	2.72	2.77	2.85
10	-4.12	57.66	2.62	2.72	2.77	2.85
11	-4.29	57.50	2.62	2.72	2.77	2.85
12	-4.00	57.60	2.63	2.73	2.78	2.86
13	-3.69	57.66	2.63	2.73	2.78	2.87
14	-3.37	57.72	2.58	2.69	2.75	2.83
15	-3.04	57.67	2.55	2.66	2.71	2.80
16	-2.71	57.69	2.51	2.62	2.68	2.77
17	-2.37	57.68	2.44	2.56	2.62	2.71
18	-2.03	57.69	2.38	2.49	2.55	2.64
19	-1.81	57.56	2.32	2.43	2.49	2.58
20	-1.87	57.38	2.28	2.39	2.45	2.54
21	-2.05	57.23	2.36	2.47	2.52	2.62
22	-2.11	57.05	2.55	2.66	2.72	2.81
23	-2.21	56.88	2.56	2.67	2.73	2.82
24	-2.44	56.75	2.72	2.83	2.89	2.98
25	-2.53	56.58	2.80	2.93	2.99	3.08
26	-2.80	56.48	2.83	2.96	3.02	3.11
27	-3.12	56.43	3.01	3.14	3.19	3.29
28	-2.81	56.36	2.97	3.11	3.16	3.25
29	-2.81	56.18	2.96	3.10	3.16	3.24
30	-3.12	56.13	3.05	3.19	3.25	3.33

Table 13.1: East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 1-30. Return levels are given for return periods of 10, 25, 50 and 100 years.

Site			l year return level			
Number	lat	long	l=10	l=25	l=50	l=100
31	-3.38	56.03	3.11	3.25	3.30	3.39
32	-3.70	56.05	3.15	3.29	3.35	3.43
33	-3.40	55.99	3.14	3.28	3.34	3.42
34	-3.08	55.95	3.13	3.27	3.33	3.41
35	-2.83	56.05	3.06	3.20	3.27	3.34
36	-2.51	56.01	3.02	3.16	3.23	3.30
37	-2.22	55.93	2.86	3.01	3.08	3.16
38	-2.01	55.79	2.80	2.95	3.02	3.10
39	-1.83	55.64	2.81	2.94	3.01	3.09
40	-1.61	55.51	2.91	3.04	3.10	3.19
41	-1.55	55.33	2.90	3.02	3.08	3.18
42	-1.52	55.15	2.96	3.09	3.15	3.26
43	-1.38	54.98	3.03	3.16	3.22	3.33
44	-1.31	54.80	3.08	3.21	3.28	3.39
45	-1.16	54.65	3.12	3.25	3.32	3.44
46	-0.88	54.57	3.17	3.30	3.37	3.48
47	-0.60	54.49	3.15	3.28	3.35	3.47
48	-0.42	54.34	3.19	3.32	3.40	3.52
49	-0.27	54.18	3.24	3.38	3.46	3.59
50	-0.21	54.01	3.29	3.44	3.52	3.65
51	-0.09	53.84	3.46	3.61	3.70	3.84
52	0.08	53.69	3.70	3.85	3.94	4.09
53	-0.22	53.70	5.71	5.97	6.09	6.24
54	-0.52	53.71	6.35	6.61	6.70	6.85
55	-0.23	53.66	4.10	4.27	4.36	4.52
56	0.00	53.54	4.12	4.29	4.38	4.55
57	0.21	53.42	3.91	4.07	4.18	4.35
58	0.33	53.25	3.94	4.11	4.22	4.40
59	0.27	53.07	5.47	5.77	5.87	6.03
60	0.07	52.94	4.51	4.72	4.82	5.01

Table 13.2: East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 31-60. Return levels are given for return periods of 10, 25, 50 and 100 years.

Site			l year return level			
Number	lat	long	l=10	l=25	l=50	l=100
61	0.31	52.81	4.73	4.93	5.04	5.24
62	0.50	52.95	4.72	4.90	5.03	5.24
63	0.79	52.97	4.49	4.70	4.83	5.06
64	1.09	52.96	3.97	4.19	4.33	4.57
65	1.38	52.91	3.49	3.73	3.88	4.13
66	1.62	52.78	3.44	3.67	3.81	4.06
67	1.74	52.62	3.21	3.44	3.58	3.81
68	1.73	52.44	2.55	2.77	2.90	3.12
69	1.63	52.26	2.47	2.69	2.81	3.02
70	1.58	52.08	2.48	2.69	2.81	3.01
71	1.37	51.96	2.79	2.98	3.10	3.28
72	1.07	51.95	3.05	3.23	3.34	3.52
73	1.13	51.77	3.13	3.31	3.42	3.58
74	0.84	51.74	3.45	3.63	3.74	3.90
75	0.87	51.56	4.43	4.61	4.71	4.88
76	0.58	51.54	4.03	4.20	4.31	4.48
77	0.30	51.47	4.07	4.25	4.35	4.51
78	0.59	51.48	4.29	4.47	4.57	4.73
79	0.87	51.42	4.06	4.24	4.34	4.50
80	1.15	51.37	3.69	3.87	3.96	4.13
81	1.44	51.38	3.59	3.76	3.86	4.02
82	1.40	51.21	3.30	3.47	3.56	3.72
83	1.20	51.08	3.95	4.12	4.21	4.37

Table 13.3: East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 61-83. Return levels are given for return periods of 10, 25, 50 and 100 years.

Site			l year return level			
Number	lat	long	l=250	l=500	l=1000	l=10000
1	-3.08	58.43	2.52	2.56	2.60	2.72
2	-3.20	58.32	2.52	2.56	2.60	2.72
3	-3.47	58.21	2.60	2.64	2.68	2.80
4	-3.72	58.08	2.67	2.70	2.75	2.87
5	-3.98	57.97	2.75	2.79	2.83	2.95
6	-4.27	57.87	2.79	2.83	2.87	2.99
7	-3.94	57.84	2.82	2.85	2.90	3.02
8	-4.16	57.69	2.82	2.86	2.90	3.03
9	-4.43	57.58	2.91	2.95	3.00	3.13
10	-4.12	57.66	2.92	2.96	3.01	3.15
11	-4.29	57.50	2.93	2.97	3.02	3.16
12	-4.00	57.60	2.94	2.98	3.03	3.19
13	-3.69	57.66	2.95	2.99	3.05	3.21
14	-3.37	57.72	2.92	2.96	3.02	3.20
15	-3.04	57.67	2.89	2.94	3.00	3.19
16	-2.71	57.69	2.86	2.91	2.98	3.17
17	-2.37	57.68	2.80	2.85	2.92	3.13
18	-2.03	57.69	2.74	2.79	2.86	3.06
19	-1.81	57.56	2.67	2.73	2.79	3.00
20	-1.87	57.38	2.63	2.69	2.76	2.96
21	-2.05	57.23	2.71	2.76	2.83	3.03
22	-2.11	57.05	2.90	2.95	3.02	3.22
23	-2.21	56.88	2.91	2.96	3.02	3.22
24	-2.44	56.75	3.07	3.12	3.19	3.39
25	-2.53	56.58	3.17	3.21	3.28	3.48
26	-2.80	56.48	3.19	3.24	3.31	3.51
27	-3.12	56.43	3.39	3.44	3.51	3.73
28	-2.81	56.36	3.33	3.38	3.45	3.64
29	-2.81	56.18	3.33	3.38	3.44	3.63
30	-3.12	56.13	3.41	3.46	3.52	3.71

Table 13.4: Return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 1-30. Return levels are given for return periods of 250, 500, 1000, 10000 years.

Site			l year return level			
Number	lat	long	l=250	l=500	l=1000	l=10000
31	-3.38	56.03	3.47	3.51	3.57	3.75
32	-3.70	56.05	3.51	3.56	3.61	3.79
33	-3.40	55.99	3.50	3.54	3.60	3.78
34	-3.08	55.95	3.49	3.53	3.59	3.76
35	-2.83	56.05	3.42	3.46	3.51	3.68
36	-2.51	56.01	3.38	3.42	3.47	3.63
37	-2.22	55.93	3.23	3.27	3.32	3.48
38	-2.01	55.79	3.17	3.21	3.26	3.41
39	-1.83	55.64	3.17	3.21	3.26	3.43
40	-1.61	55.51	3.27	3.32	3.39	3.58
41	-1.55	55.33	3.27	3.32	3.39	3.60
42	-1.52	55.15	3.35	3.41	3.48	3.70
43	-1.38	54.98	3.43	3.49	3.57	3.80
44	-1.31	54.80	3.49	3.55	3.63	3.87
45	-1.16	54.65	3.54	3.61	3.69	3.94
46	-0.88	54.57	3.59	3.65	3.74	3.99
47	-0.60	54.49	3.58	3.65	3.73	4.00
48	-0.42	54.34	3.64	3.71	3.80	4.10
49	-0.27	54.18	3.71	3.78	3.88	4.19
50	-0.21	54.01	3.78	3.86	3.96	4.30
51	-0.09	53.84	3.97	4.06	4.17	4.52
52	0.08	53.69	4.23	4.32	4.43	4.81
53	-0.22	53.70	6.38	6.47	6.59	6.98
54	-0.52	53.71	7.00	7.10	7.22	7.64
55	-0.23	53.66	4.69	4.79	4.93	5.40
56	0.00	53.54	4.72	4.83	4.98	5.50
57	0.21	53.42	4.54	4.65	4.81	5.39
58	0.33	53.25	4.60	4.72	4.90	5.53
59	0.27	53.07	6.21	6.32	6.47	7.05
60	0.07	52.94	5.21	5.35	5.53	6.24

Table 13.5: East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 31-60. Return levels are given for return periods of 250, 500, 1000, 10000 years.

Site			l year return level			
Number	lat	long	l=250	l=500	l=1000	l=10000
61	0.31	52.81	5.45	5.60	5.80	6.56
62	0.50	52.95	5.48	5.63	5.85	6.68
63	0.79	52.97	5.32	5.48	5.71	6.57
64	1.09	52.96	4.83	5.00	5.23	6.06
65	1.38	52.91	4.39	4.55	4.77	5.57
66	1.62	52.78	4.30	4.46	4.66	5.37
67	1.74	52.62	4.04	4.19	4.37	5.01
68	1.73	52.44	3.34	3.48	3.65	4.23
69	1.63	52.26	3.23	3.36	3.52	4.05
70	1.58	52.08	3.21	3.33	3.48	3.97
71	1.37	51.96	3.47	3.57	3.72	4.16
72	1.07	51.95	3.69	3.80	3.93	4.35
73	1.13	51.77	3.75	3.85	3.98	4.37
74	0.84	51.74	4.07	4.17	4.29	4.69
75	0.87	51.56	5.05	5.14	5.27	5.67
76	0.58	51.54	4.64	4.74	4.86	5.25
77	0.30	51.47	4.67	4.77	4.89	5.28
78	0.59	51.48	4.90	4.99	5.11	5.50
79	0.87	51.42	4.66	4.75	4.88	5.26
80	1.15	51.37	4.29	4.38	4.50	4.88
81	1.44	51.38	4.18	4.27	4.39	4.76
82	1.40	51.21	3.87	3.96	4.08	4.44
83	1.20	51.08	4.52	4.61	4.73	5.09

Table 13.6: East coast spatial return level estimates, in metres relative to mean sea-level in 1990, obtained from the spatial model for the east coast grid: sites 61-83. Return levels are given for return periods of 250, 500, 1000, 10000 years.

Table 13.7: Estimates of the 100 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method.

Site	nyr	CT90 Marg	se	CT90 Spat	se	Method IV
Ullapool	12	4.04	0.46	4.49	0.14	3.57
Gourock	56	3.26	0.13	3.60	0.13	3.42
Ardrossan	35	3.22	0.41	3.22	0.13	3.53
Silloth	40	6.72	0.18	6.67	0.12	6.13
Barrow	19	6.39	0.60	6.39	0.13	6.82
Heysham	36	6.93	0.57	6.63	0.13	6.77
Fleetwood	48	6.21	0.08	6.26	0.05	6.73
Hilbre Island	80	5.78	0.09	5.77	0.05	6.19
Princes Pier	37	6.24	0.10	6.40	0.06	6.46
Georges Pier	42	6.12	0.28	6.06	0.04	6.46
Gladstone Dock	20	6.21	0.13	6.34	0.06	6.44
Eastham Lock	19	6.48	0.06	6.50	0.04	6.46
Fishguard	16	3.28	0.05	3.32	0.03	3.76
Milford Haven	26	4.69	0.18	4.42	0.03	4.68
Swansea	36	5.80	0.03	5.93	0.06	6.42
Cardiff	41	7.71	0.10	7.79	0.06	8.01
Newport	37	8.27	0.14	8.24	0.06	7.80
Avonmouth	61	8.71	0.15	8.73	0.07	7.59
Newlyn	61	3.31	0.05	3.40	0.04	3.72
Devonport	38	3.31	0.14	3.32	0.04	3.51
Portland	20	2.05	0.08	2.04	0.04	2.97
Calshot	42	2.57	0.08	2.75	0.04	2.95
Southampton	47	2.89	0.12	2.90	0.03	2.95
Portsmouth	104	3.09	0.09	3.03	0.03	3.19
Newhaven	60	4.21	0.06	4.37	0.04	4.70
Pevensey	24	4.89	0.16	4.86	0.04	5.15
Rye	4	5.06	0.31	4.95	0.06	5.30
Dover	62	4.82	0.30	4.75	0.09	4.91
Margate	10	5.04	3.68	3.58	0.09	4.25
Southend	57	4.53	0.24	2.90	0.03	2.95

Table 13.8: Estimates of the 100 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method.

Site	nyr	CT90 Marg	se	CT90 Spat	se	Method IV
Sheerness	136	4.48	0.15	4.44	0.08	4.56
Tilbury	46	5.25	0.44	5.03	0.09	4.56
Tower Pier	49	5.75	0.30	5.73	0.09	4.51
Colchester	43	4.22	0.18	4.55	0.09	4.27
Holland-on-Sea	53	4.39	0.54	3.89	0.09	4.06
Walton-on-the-Naze	15	3.28	0.39	3.56	0.10	3.99
Harwich	51	3.92	0.27	3.78	0.09	3.82
Lowestoft	31	3.52	0.49	3.06	0.07	3.37
Gt. Yarmouth	77	3.20	0.29	2.90	0.07	3.74
Kings Lynn	119	5.77	0.18	5.72	0.08	5.75
Wisbech Cut	22	5.95	0.59	5.71	0.08	5.79
Marsh Road Sluice	17	6.63	0.70	6.31	0.08	5.83
Lawyers Sluice	26	6.15	0.71	5.66	0.08	5.85
Boston	59	5.65	0.15	5.89	0.08	5.85
Grimsby	54	4.38	0.16	4.65	0.08	4.92
Immingham	69	4.92	0.14	4.97	0.08	4.93
Saltend Jetty	13	6.42	2.45	5.22	0.05	4.77
Humber Dock	42	4.97	0.15	5.01	0.04	4.79
St. Andrews Dock	49	5.17	0.11	5.26	0.04	4.81
Victoria Dock	24	5.13	0.18	5.12	0.04	4.79
King Georges Dock	36	5.11	0.21	5.01	0.05	4.77
Blacktoft	56	5.67	0.09	5.72	0.05	4.86
Brough	56	5.57	0.10	5.63	0.04	4.82
Goole	59	5.92	0.06	6.01	0.06	4.91
North Shields	35	5.33	2.06	3.79	0.09	3.92
Kirkcaldy	28	3.65	0.16	3.65	0.05	3.99
Methil	38	4.05	0.14	4.10	0.06	4.00
Leith	38	3.70	0.10	3.79	0.05	3.99
Rosyth	31	3.98	0.14	4.12	0.07	3.98
Grangemouth	34	4.38	0.16	4.35	0.10	3.98
Aberdeen	67	3.07	0.08	3.13	0.06	3.27

Table 13.9: Estimates of the 1000 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method.

Site	nyr	CT90 Marg	se	CT90 Spat	se	Method IV
Ullapool	12	4.24	0.74	5.06	0.31	3.77
Gourock	56	3.43	0.22	4.16	0.30	3.86
Ardrossan	35	3.38	0.50	3.79	0.29	3.98
Silloth	40	6.97	0.28	7.24	0.29	6.55
Barrow	19	7.30	1.94	6.96	0.30	7.38
Heysham	36	8.13	1.84	7.20	0.30	7.33
Fleetwood	48	6.30	0.10	6.45	0.09	7.29
Hilbre Island	80	5.96	0.16	5.96	0.08	6.70
Princes Pier	37	6.31	0.08	6.58	0.09	7.00
Georges Pier	42	6.33	0.34	6.21	0.07	7.00
Gladstone Dock	20	6.25	0.14	6.52	0.09	6.98
Eastham Lock	19	6.49	0.06	6.53	0.06	7.00
Fishguard	16	3.29	0.05	3.36	0.04	4.04
Milford Haven	26	4.72	0.18	4.47	0.05	4.96
Swansea	36	5.81	0.03	6.00	0.09	6.70
Cardiff	41	7.86	0.14	8.03	0.10	8.34
Newport	37	8.50	0.24	8.49	0.10	8.14
Avonmouth	61	8.90	0.22	9.00	0.11	7.95
Newlyn	61	3.38	0.07	3.52	0.06	3.99
Devonport	38	3.41	0.23	3.46	0.06	3.87
Portland	20	2.16	0.13	2.18	0.06	3.57
Calshot	42	2.61	0.09	2.91	0.06	3.50
Southampton	47	3.04	0.20	3.05	0.06	3.50
Portsmouth	104	3.35	0.20	3.19	0.06	3.75
Newhaven	60	4.27	0.08	4.53	0.07	5.12
Pevensey	24	4.97	0.19	5.09	0.07	5.55
Rye	4	5.46	0.74	5.13	0.08	5.71
Dover	62	5.69	0.83	5.36	0.20	5.39
Margate	10	10.41	19.61	4.19	0.20	4.83
Southend	57	5.09	0.53	3.05	0.06	3.50

Table 13.10: Estimates of the 1000 year return level for the annual maximum sites analysed in Coles and Tawn (1990). The column abbreviations are: nyr, the number of years of data at the site; CT90 Marg, estimates obtained from the marginal annual maximum method; CT90 SPat, estimates obtained from the spatial annual maximum method.

Site	nyr	CT90 Marg	se	CT90 Spat	se	Method IV
Sheerness	136	5.06	0.35	5.05	0.20	5.05
Tilbury	46	6.23	1.25	5.64	0.20	5.05
Tower Pier	49	6.40	0.74	6.33	0.20	5.02
Colchester	43	4.45	0.37	5.15	0.20	4.75
Holland-on-Sea	53	5.86	1.74	4.40	0.17	4.56
Walton-on-the-Naze	15	3.68	0.90	4.07	0.17	4.49
Harwich	51	4.63	0.63	4.29	0.16	4.32
Lowestoft	31	4.54	1.24	3.61	0.15	3.87
Gt. Yarmouth	77	3.93	0.67	3.45	0.15	4.24
Kings Lynn	119	6.44	0.44	6.26	0.15	6.18
Wisbech Cut	22	7.01	1.73	6.25	0.16	6.21
Marsh Road Sluice	17	7.69	1.90	6.83	0.10	6.25
Lawyers Sluice	26	7.37	1.97	6.18	0.15	6.27
Boston	59	5.98	0.32	6.40	0.15	6.27
Grimsby	54	4.66	0.27	5.08	0.15	5.28
Immingham	69	5.23	0.30	5.39	0.15	5.29
Saltend Jetty	13	10.84	14.97	5.44	0.10	5.13
Humber Dock	42	5.11	0.21	5.24	0.08	5.16
St. Andrews Dock	49	5.34	0.23	5.47	0.07	5.17
Victoria Dock	24	5.31	0.37	5.34	0.08	5.15
King Georges Dock	36	5.53	0.49	5.20	0.09	5.14
Blacktoft	56	5.83	0.14	5.92	0.09	5.23
Brough	56	5.71	0.18	5.84	0.07	5.18
Goole	59	5.99	0.07	6.21	0.12	5.27
North Shields	35	15.24	18.51	4.03	0.15	4.25
Kirkcaldy	28	3.83	0.29	3.86	0.10	4.19
Methil	38	4.26	0.30	4.31	0.10	4.19
Leith	38	3.79	0.15	4.01	0.10	4.20
Rosyth	31	4.11	0.23	4.39	0.13	4.20
Grangemouth	34	4.66	0.27	4.68	0.18	4.21
Aberdeen	67	3.22	0.13	3.33	0.11	3.47