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Changes to estimates of extreme sea levels for Wales
when data from the 2013/2014 winter are included

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Report for Natural Resources Wales

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DOCUMENT DATA SHEET

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1. BACKGROUND

Extreme sea levels at coastal locations depend upon tidal processes and the co-occurrence of storm surges – the effect of transient weather systems on the sea surface. An accepted method for combining the deterministic tidal distributions with stochastic storm surge distributions is the joint probability method (JPM). This was initially proposed by Pugh and Vassie (1980) as an improvement on fitting an extreme value distribution to either annual maximum sea levels, or a fixed number of extreme levels in each year (the so-called r-largest approach). At a given location one can calculate the joint probability table for all combinations of tide and non-tidal residual within an observational record (e.g. from a tide gauge).

Joint probability methods make the most efficient use of all recorded sea level data, and yield probabilities that have less dependence on extrapolation. However – as with any statistical method – the accuracy and timing of observations must be of high quality. In all previous research concerned with estimating extreme sea levels using joint probability methods the quantity examined was the non-tidal residual (i.e. the time series obtained by subtracting tidal predictions from the data measured by the tide gauge). Many properties of the residual time series can be shown to be an artifact of small changes to the timing of high water. It is well known that at many locations peak non-tidal residuals are obtained 3-5 hours before tidal high water (Horsburgh and Wilson, 2007). Both strong winds and perturbations of atmospheric pressure in weather systems can dynamically alter the timing of high water and low water by tens of minutes, without any change to the actual peak levels; small inaccuracies in tidal prediction alone can result in an incomplete specification of high water timing. Consequently, any analysis of non-tidal residual maxima has little scientific or engineering significance. A more robust measure of storm surge is needed to produce reliable statistics.

In recent work conducted for the Coastal Flood Boundary Data (CFBD) project (Batstone et al., 2013; McMillan et al., 2010) we calculated the joint probabilities of tide and *skew surge*. The skew surge is simply the difference between the elevation of the predicted astronomical high tide and the actual observed high water within a tidal cycle. As such it is an integrated effect of the weather over a full tidal cycle and it measures properly the additional elevation of the sea surface due to a storm. It is the preferred surge diagnostic for the Dutch operational system (e.g. de Vries et al., 1995) and is of far greater practical significance than maximum residual. It is now the preferred measure of storm surge for UK operational analysis. As a final step, in the CFBD project we combined the extreme sea level estimates derived at tide gauge sites with long runs of well-validated numerical models in order to provide a consistent spatial statistical method for extreme sea level around the entire UK coastline.

The storms that affected the UK during December 2013 and January 2014 marked some of the most severe weather in recent years, giving rise to high sea levels and extreme waves around the entire coastline. During the 5^{th} and 6^{th} December, sea levels in parts of the North Sea were the highest since the 1953 floods and the Thames Barrier and Dutch flood barriers were closed for several tides. The 5/6 December 2013 storm surge was the largest coastal flood incident for 60 years for parts of Wales and also the east coast; at Liverpool, the sea level was the largest observed for 30 years (although one must remember that records are always in the context of the length of data available). The 2013/2014 sequence of storms gave rise to the largest storm surges ever observed at Fishguard, Barmouth and Holyhead (Haigh et al., 2015). The storm surge at

Fishguard on 14 February 2014 was calculated by Haigh et al. (2015) as the 1 in 87 year level. The winter of 2013-2014 begs the obvious question of whether the return levels tabulated in McMillan et al. (2010) would be different had the more recent data been included in the statistical analysis. This short report provides a re-analysis of the extreme sea level estimates for seven locations around, or close to, the Welsh coastline (Liverpool, Llandudno, Barmouth, Milford Haven, Mumbles, Newport and Avonmouth) in order to confirm confidence in the return levels that were estimated in 2010.

2. SYNTHESIS OF RESULTS

In the figures that follow, the dark blue squares and lines denote our re-estimates of the return levels using tide gauge data up to 2008 (for consistency with the work of McMillan et al., 2010). The red circles and lines show our analysis of the return levels with all tide gauge data up to December 2014. For the purposes of this exercise, the significant changes we are interested in are therefore any differences between these symbols (blue squares and red circles). The light blue lines, where shown, are the results from the original CFBD project as reported in McMillan et al. (2010). Our re-estimates do not always overlie the published 2010 results perfectly for a number of reasons: the origin of the quality controlled data; the method of de-tiding used; the spatial choice of statistical parameters used to fit the skew surge distribution. Finally, the black diamond symbols (AMAX) show the highest annual maxima from the raw data. These are for information only but can help provide a “sanity check” on statistical methods.

Table 1. Changes to 100, 200 and 1000 year return levels with associated confidence intervals

	Change to 100 year level (cm)	Confidence interval (cm)	Change to 200 year level (cm)	Confidence interval (cm)	Change to 1000 year level (cm)	Confidence interval (cm)
Liverpool	+2	20	0	20	-8	30
Llandudno	+3	20	+1	20	-5	30
Barmouth	+5	20	+5	20	+5	30
Milford Haven	0	20	0	20	0	30
Mumbles	0	20	+4	30	+8	50
Newport	+6	20[1]	+10	30[1]	+13	50[1]
Avonmouth	+6	20[1]	+10	30[1]	+18	50[1]

[1]McMillan et al. (2010) did not calculate confidence intervals for Newport or Avonmouth. However since these locations share a similar high tidal range as Mumbles and are in the same confined geographical region (Bristol Channel) then it is reasonable to take the confidence intervals for Mumbles as a good estimate

Table 1 summarises the changes in 100, 200 and 1000 year return level when the data up to December 2014 are included (a positive value means the return level estimate is higher with the more recent data included). Confidence intervals for each return level are given. The confidence intervals are calculated using the methods described in section A6.2 of McMillan et al. (2010). Randomisation of the skew surge time series was used to statistically generate 95% confidence intervals (2.5 to 97.5 percentiles). The figures are then presented in Table A6.3 of McMillan et al. (2010) in a more practical way so that users can simply interpret the confidence interval as plus or minus that value from the central estimate. For example, if the 200 year return level for a location is 5m and the confidence interval is 0.2m then one can treat the 200 year level as 5.0 ±

0.2m. The figures used in Table 1 here are taken directly from Table A6.3 of McMillan et al. (2010) where available.

The inclusion of the most recent data does not make a statistically significant difference to the return levels for Welsh ports. Including the additional data results in small positive changes to all return levels (except for Liverpool and Llandudno at the 1000 year return level). However, all changes are considerably smaller than the 95% confidence intervals for those levels as reported by McMillan et al. (2010). To place the result into context, Table 2 shows the 200 year return level calculated by the original CFBD project, the confidence interval, and the change from our revised estimate.

Table 2. 200 year return level from McMillan et al. (2010), confidence interval, and change due to 2013/2014 data

	200 year level (m)	Change to 200 year level (m)	95% confidence interval (m)
Liverpool	6.03	0	0.2
Llandudno	5.38	+0.01	0.2
Barmouth	4.22	+0.05	0.2
Milford Haven	4.75	0	0.2
Mumbles	6.15	+0.04	0.3
Newport	8.41	+0.10	0.3
Avonmouth	9.11	+0.10	0.3

Taking into consideration that the December 2013 storm had a unique spatial footprint (i.e. its severity would have differed depending on exact geographic location) then it is not surprising that the inclusion of new data has made no changes to the statistical modelling at some locations (e.g. Milford Haven). Where small changes were obtained, their magnitude is well within the 95% confidence interval and we can conclude that return levels are not significantly affected by the inclusion of the more recent data (although obviously they should be more robust due to its inclusion).

Finally, Figure 8 demonstrates the sensitivity of the return level estimation process (i.e. the overall method) to very small changes in parameters used in the analysis. We take Llandudno as an example but the size of the sensitivity scales with the tidal range of the location. The matrix shows that we take multiple combinations of various choices: we compare two downloaded versions of the raw data from BODC (over the full time span to 2014); we use two different but equally valid methods of tidal prediction; we use three derivations of the 18.6 year probability distribution function of peak tides; finally we perturb a simple parameter used to create return period curves from the raw data. The last figure shows the overall effect with different coloured symbols representing choices from the matrix. We see that even these small perturbations – equally valid choices of data selection or tidal analysis – can result in an approximate 10cm difference for the 200 year return level and a 15cm difference for the 1000 year return level at Llandudno. This highlights the fact that statistical methods for estimating extreme sea levels are (a) completely data driven and (b) are sensitive to numerous assumptions within the overall process. It also explains why the curves shown in Figures 1-7 can, in some cases, differ from the

CFBD curves. It should be noted that the effects we demonstrate in this small experiment are still within the confidence intervals that have been previously published: those confidence intervals are therefore reliable guides to uncertainty.

Conclusions

We conclude that re-estimating the return levels for this selection of ports around the coastline of Wales, using the methods of McMillan et al. (2010), does not significantly change those return levels. It would be reasonable to extrapolate this, and any other conclusions, to the entire Welsh coastline since those tide gauge sites are (a) the best data available and (b) well distributed around the entire coastline. The tests we performed show how sensitive return level estimates are to even very small changes (of order 1cm) in the tide gauge data or the methods used to predict a full probability distribution function of the tide alone. Whilst the approach taken in McMillan et al. (2010) is best practice and represents the most consistent and reliable published set of extreme sea level estimates around the entire coastline, further improvements are possible with additional research. Two areas of potential improvement motivated by scientific advances are: (a) further refinement of the statistical model by rigorously selecting the number of statistical parameters needed (e.g. by using Bayesian Information Criteria); (b) including the seasonal dependencies of storm surges and tides. These refinements could lead to improved spatial consistency of the return levels and also reductions in uncertainty.

FIGURES (tide gauge sites are presented counter-clockwise around the Welsh coast)

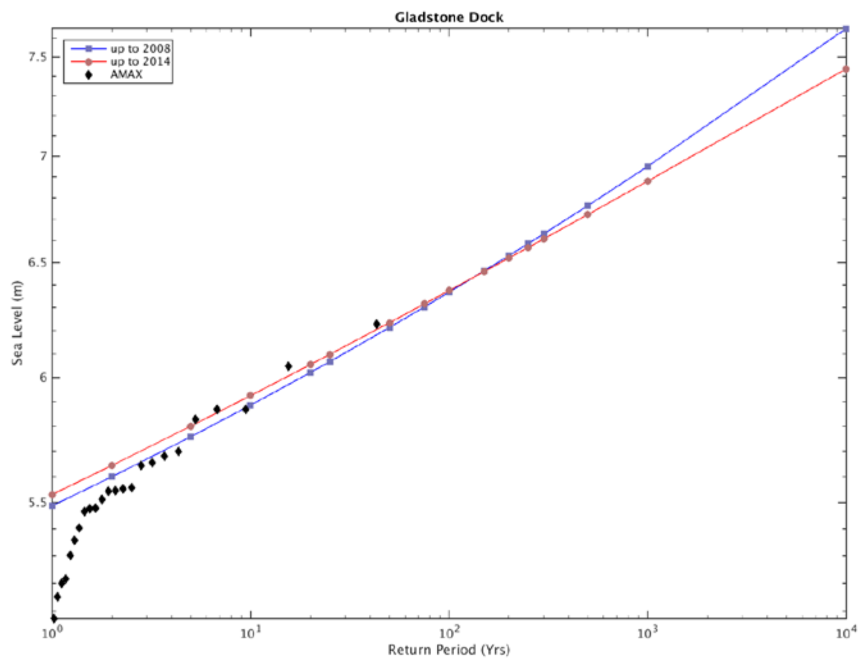

Figure 1. Return levels for Liverpool tide gauge

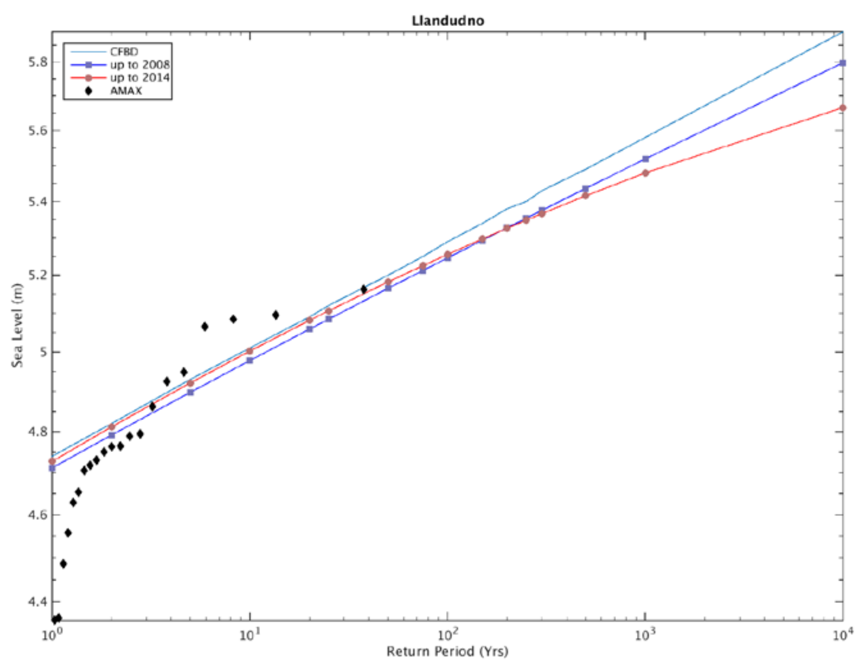

Figure 2. Return levels for Llandudno tide gauge

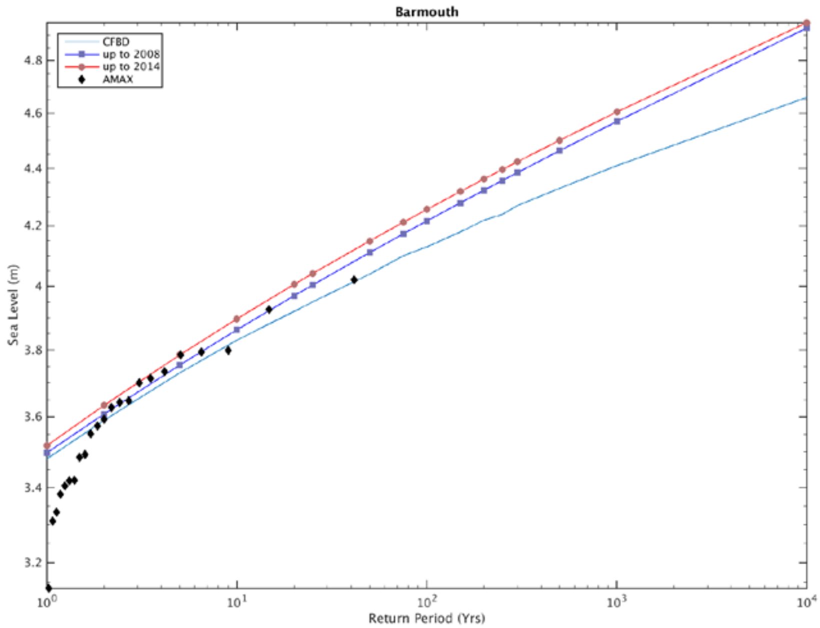

Figure 3. Return levels for Barmouth tide gauge

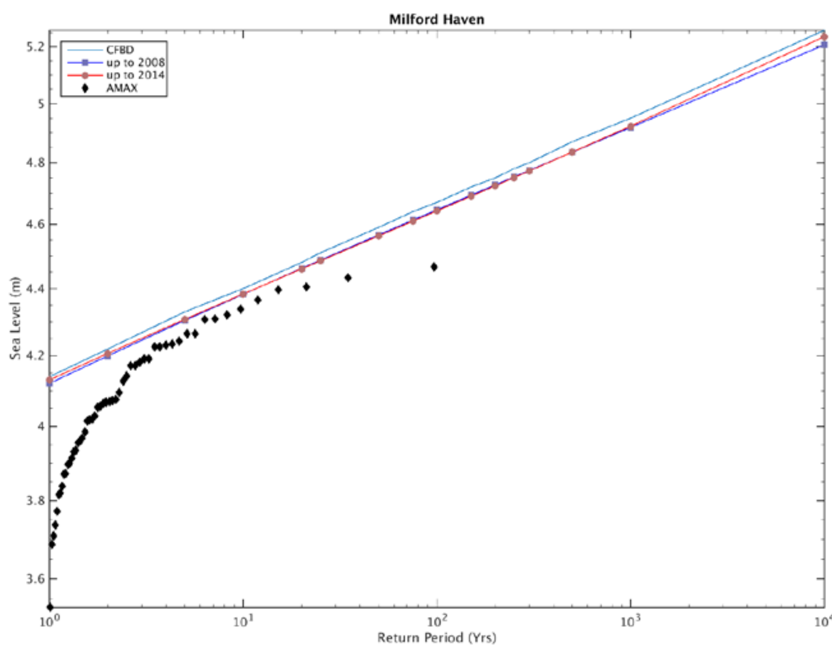

Figure 4. Return levels for Milford Haven tide gauge

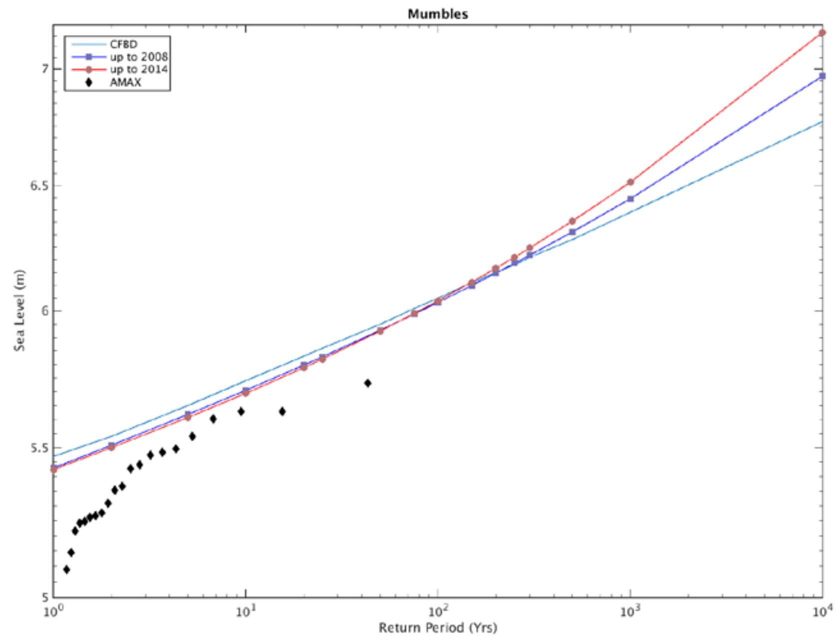

Figure 5. Return levels for Mumbles tide gauge

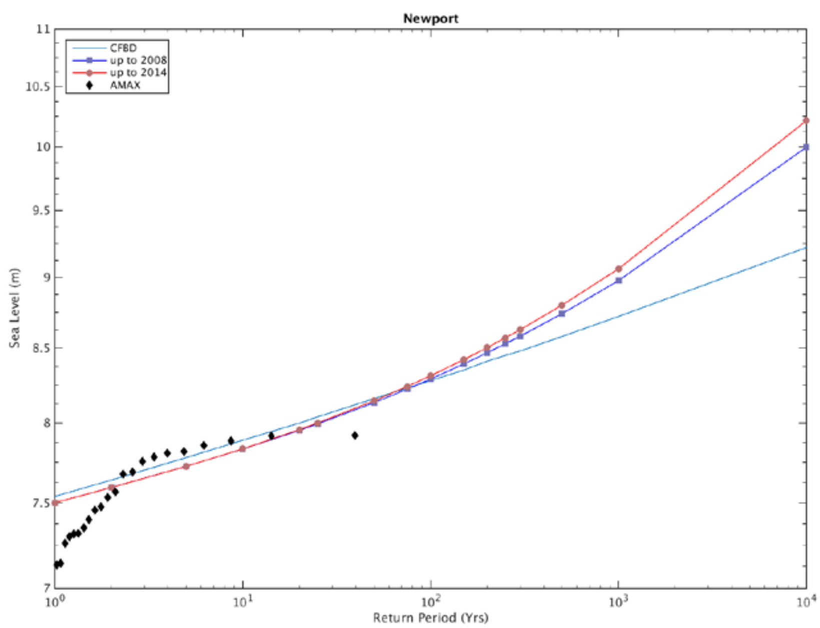

Figure 6. Return levels for Newport tide gauge

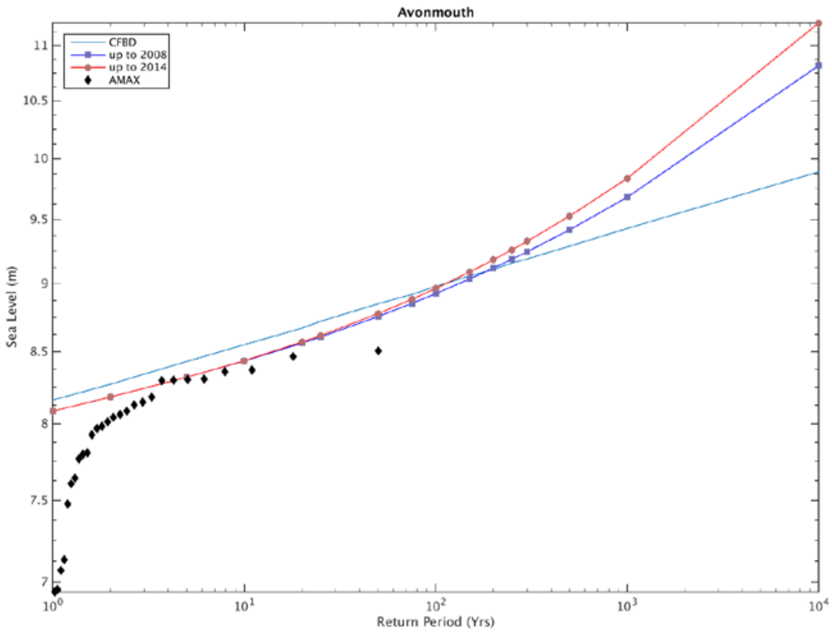

Figure 7. Return levels for Avonmouth tide gauge

Llandudno Test

	Data		Tides		Peak Tides			Polynomial Degree	
	BODC	Original	Tidefit	Original	Tidefit	Alt1	Alt2	2	3
1	■		■		■			■	
2		■		■	■			■	
3		■		■		■		■	
4		■		■			■	■	
5	■		■			■		■	
6	■		■				■	■	
7	■		■		■				■
8		■		■	■				■
9	■			■	■				■
10		■	■		■				■

Notes

1. Data. BODC refers to the quality controlled dataset that is available from the British Oceanographic Data Centre (BODC). “Original” refers to the data used during the CFBD project that had additional QC and manual editing as described in M McMillan et al. (2010)
2. Two programs were available for tidal analysis of the data set. NOC has recently created an improvement to the standard tidal analysis program which is used routinely. This new program, NOCtidefit, calculates astronomical arguments for tides more frequently than the standard one
3. As per 2 but for the identification of all the individual high water within an 18.6 year nodal cycle
4. Polynomial degree: 2/3 determines the shape of the plotted return period curves from which return levels are then interpolated and extracted.

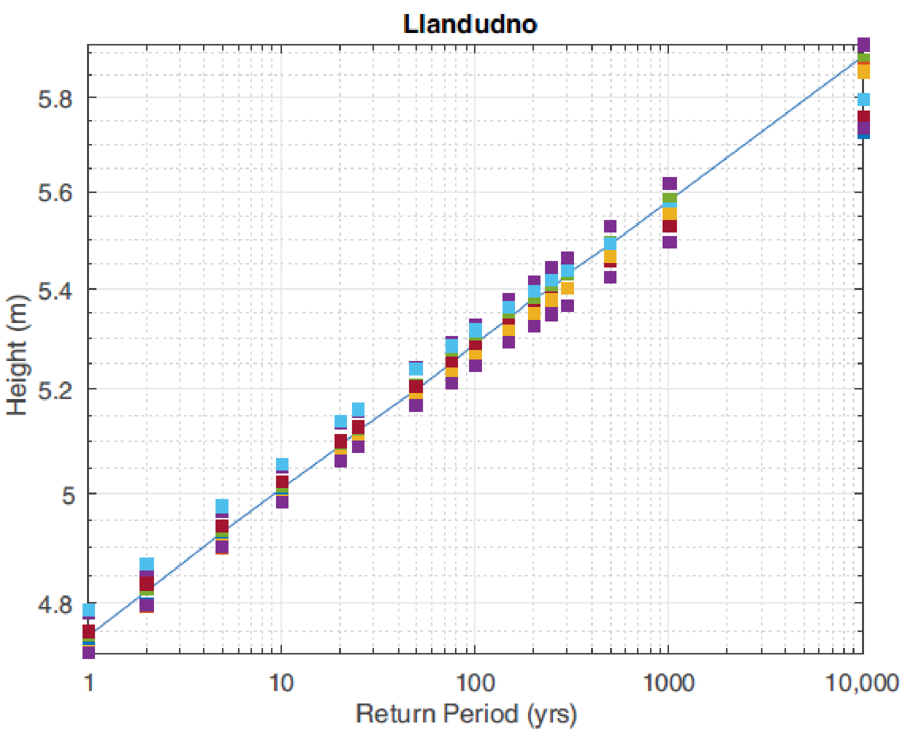

Figure 8. Sensitivity of the estimation process (shown for Llandudno) to very small changes in parameters used in the analysis

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