24-Jul-2018

Extreme Sea Levels at Christchurch Sites: EV1 Analysis

1. Introduction

Since 2010[1] when the last analysis of extreme sea levels was carried out, there have been 5 independent events when sea levels exceeded 10.81 m above CDB datum at Bridge St, four of them since Jun-2017. The purpose of this study was to update the statistics to include these events.

In the initial work of this update, Pareto distributions were fitted to the peaks over a threshold at each site. The reason for using this method was that in the period from Apr-2017 to Feb-2018, four independent events have occurred at Bridge St which with one other separate event make up the five highest events at the site. Thus, if the traditional GEV[2] method using annual maxima were used, only at most two of these events would be included in the analysis. However, the Pareto distributions that best fit the data, while adequate for return periods less than 100 years, gave unreasonable results when extrapolated for periods greater than 100 years.

Maximum sea levels are a summation of tide and storm surge. Tide heights have a maximum (called HAT- highest astronomical tide) that is never exceeded, while storm surge around New Zealand is generally less than 1 m in height. Therefore, sea levels greater than 1 m over HAT are unlikely to ever occur for practical reasons, yet the Pareto distributions gave levels exceeding this, meaning that the Pareto distributions could not be used for extrapolation beyond 100 years. Yet the 500-y return period levels are used by CCC for planning purposes.

In a review of the original work by Charles Pearson of NIWA, the suggestion was made to re-calculate the return periods using annual maxima and the EV1 distribution (also known as the Gumbel distribution). The argument was made that for periods of record exceeding 20 years (which applies to all of the sites under consideration), annual maxima contain sufficient information to legitimately fit a curve, even with the prevalence of events in the last year of record. And by assuming that 2-Feb-2018 event represents that largest event for 2018, this event and the event of 21-Jul-2017 would be included in the analysis.

Therefore, this report presents the results of fitting the EV1 distribution to annual maxima from each site.

The Annex to this report contains a description of the process of establishing the best available set of storm tides at Sumner Head using the NIWA gauge in association with GeoNet's tsunami gauge and the tide gauge in Lyttelton Harbour, with allowance for long-period waves that affect the sea levels.

1 Goring, D. G. 2010: Downstream hydraulic boundary conditions for Avon and Heathcote Rivers. Mulgor Technical Note Nov. 2010.

2 GEV = Generalised Extreme Value

2. Data and Methods

2.1 Data

The available data are listed in Table 1. For each of these records, the times of high tide were hindcast using the tidal constituents from Goring (2018)[3] and the maximum sea level within an hour either side of high tide was extracted. This is the storm-tide level. The percentage of gaps listed in Table 1 is the percentage of high tides that were missing for each site.
The datum used for all sites was Christchurch Drainage Board (CDB) which is 9.043 above Lyttelton Vertical Datum (1931).

Station	**Start**	**Finish**	**No. yrs**	**% Gaps**
Sumner Head	03-Jun-1994	16-Feb-2018	23.7	2.6
Avon @ Bridge St	18-Sep-1997	16-Feb-2018	20.4	7.7
Heathcote @ Ferrymead	01-Jan-1974	16-Feb-2018	44.1	6.4
Styx @ Tide Gates	11-Jul-1990	16-Feb-2018	27.6	8.6

The record at Sumner Head was processed to correct obvious errors and to fill gaps using the records from the GeoNet tsunami gauge SUMT and the Lyttelton Port Company tide gauge. The details are presented in the Annex.

At Styx, the event of 17-Apr-2003 stands out above all the other data and analysis by Graham Harrington of CCC indicated that the general levels at the gauge were elevated by about 0.2 m. Therefore, the peak at Styx for the event of 17-Apr-2003 was reduced by 0.2 m for the analysis.

2.2 Extreme Value Analysis

The initial step in the analysis is to ensure that the annual maxima are independent and have no trend. Statistical tests were carried out on the annual maxima from each site and the results were as follows:

- Estuary sites were found to be reasonably statistically independent.
- Sumner Head was found to have a small, positive trend. Mr Pearson advises that this trend be monitored over succeeding years to establish whether it is a real trend or statistically random.

For fitting the EV1 distribution to annual maxima, we used the method of probability weighted moments[4].

3. Results

The results for all four stations listed in Table 1 are presented in Figures 1a to d and Table 2 lists the fitted parameters, along with the details of the upper three events for each site.. The equations for the EV1 distribution are presented in Appendix I.

In all cases, the event with the highest storm tide was 02-Feb-2018, which had return periods of about 50 y for all except Ferrymead, where the event represented a 115 y return period. The

3 Goring, D. G. 2018: Factors affecting high water levels in Christchurch estuaries. Mulgor Technical Report 2018/1.

4 See e.g.: Greenwood, J.A.; Landwehr, J.M.; Matalas, N.C.; Wallis, J.R. 1979: Probability weighted moments: definition and relation to parameters of several distributions expressable in inverse form. *Water Resources Research*, 15(5): 1049-1054.

following event was on 21-Jul-2017 for all three estuary sites.

Table 2. Parameters for EV1 distribution and details of upper three events.

Parameter	**Sumner Head**	**Bridge St**	**Ferrymead**	**Styx**
Location μ	10.730	10.642	10.609	10.709
Scale σ	0.092	0.108	0.088	0.128
Event 1				
Date	02-Feb-2018	02-Feb-2018	02-Feb-2018	02-Feb-2018
Max Level	11.098	11.081	11.026	11.159
RP y	55	58	115	35
Event 2				
Date	18-Apr-2011	21-Jul-2017	21-Jul-2017	21-Jul-2017
Max Level	10.965	10.963	10.935	11.048
RP y	13	20	41	15
Event 3				
Date	22-Jul-2017	04-Mar-2014	17-Apr-1999	17-Apr-2003
Max Level	10.938	10.899	10.868	10.965
RP y	10	11	20	8

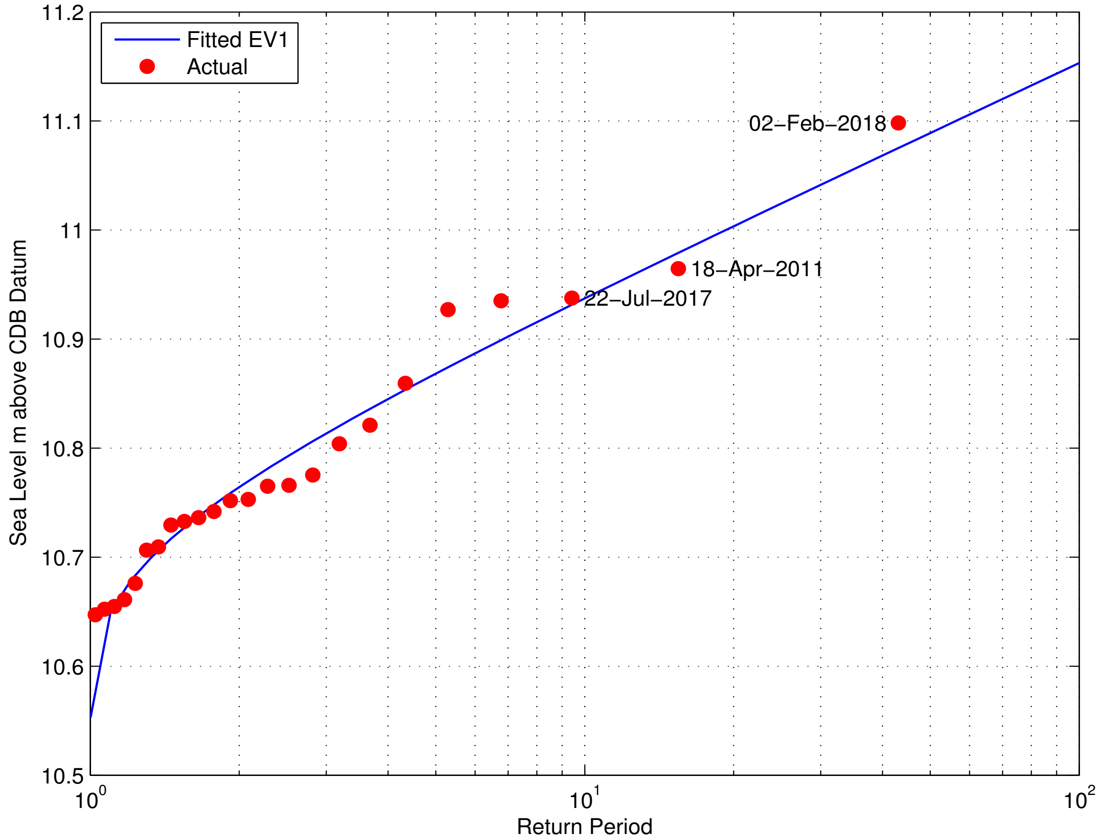

Figure 1a. EV1 distribution for Sumner Head.

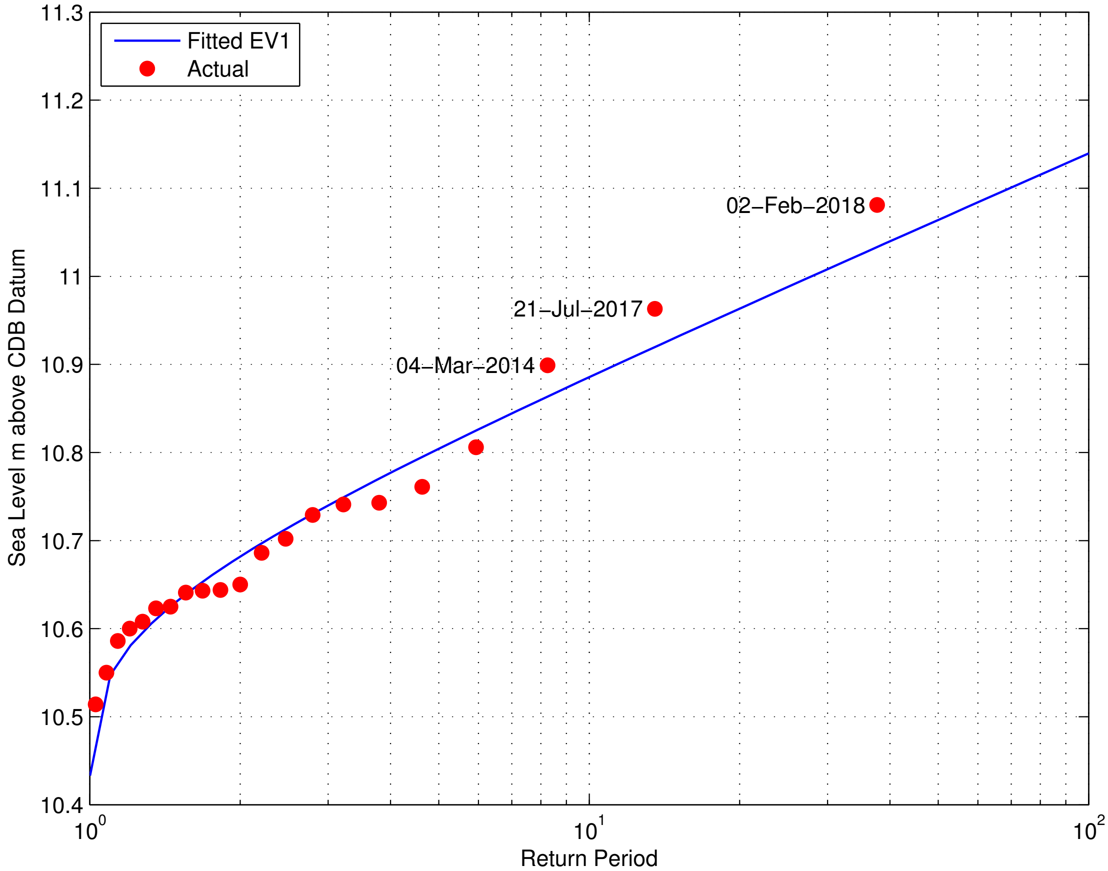

Figure 1b. EV1 distribution for Bridge St.

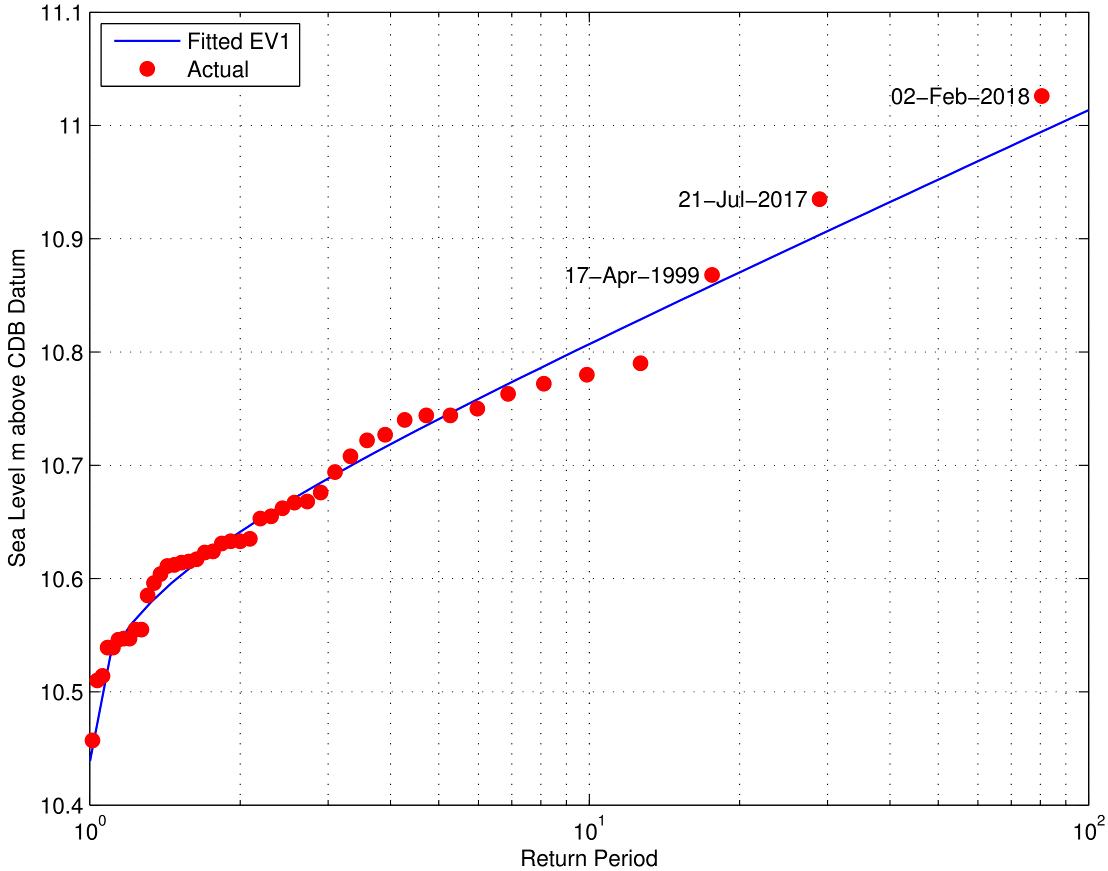

Figure 1c. EV1 distribution for Ferrymead.

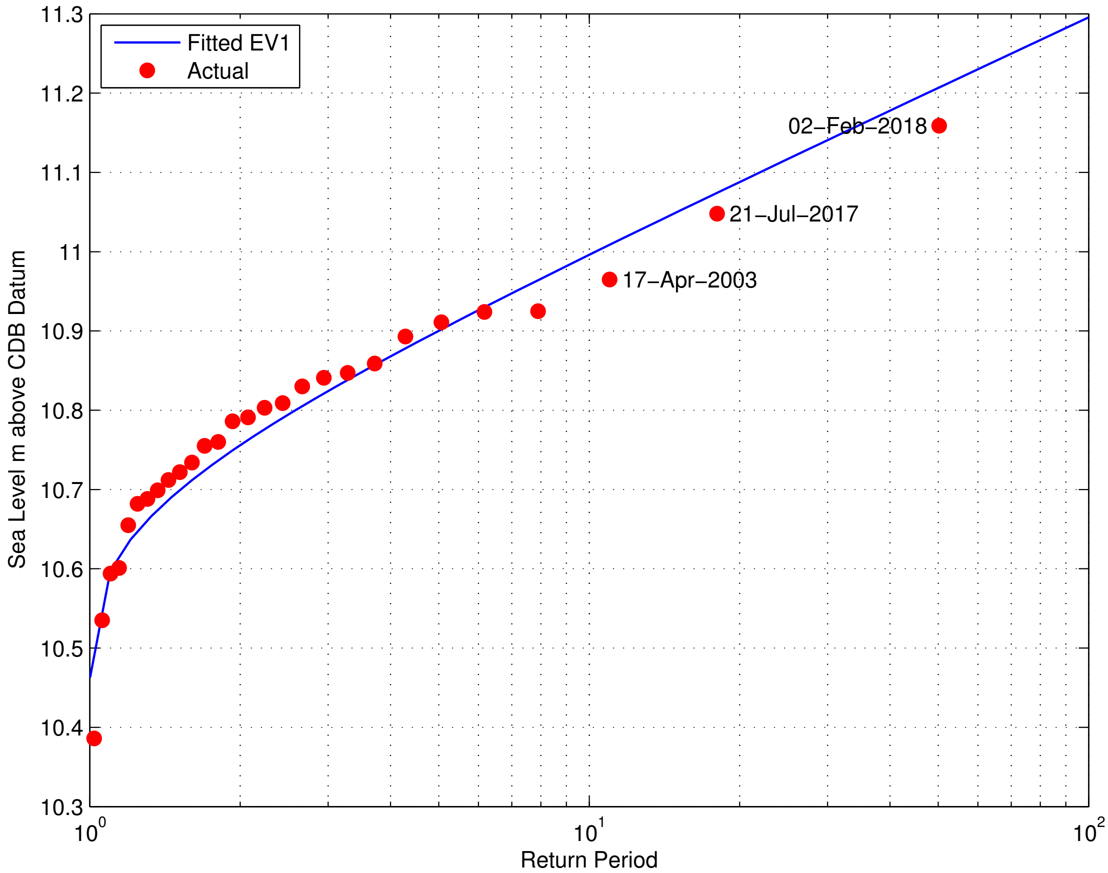

Figure 1d. EV1 distribution for Styx.

Using the distributions shown in Figures 1a to d and the parameters listed in Table 2, the storm tide levels for return periods 2 to 100 y are listed in Table 3 and summarised in Figure 2.

A noticeable feature of these results is that the levels at Ferrymead are much lower than those at Sumner Head and Bridge St. Examination of the fit of the EV1 distribution in Figure 1c shows there is a cluster of points just below 10.8 m. These could have pulled the fitted curve down, thus reducing the level of the fitted curve. Examination of the data showed that three of those points occurred prior to 1986, when the data were high and low tides digitised from a chart. The accuracy of such data is questionable. However, excluding data prior to 1986 made no significant difference to the results, so the original analysis has been retained.

Adjustment of the Styx level downwards for the event of 17-Apr-2003, reducing its importance from first to third, has not changed the position of the Styx curve above the other curves.

Table 3. Storm tide levels (m above CDB datum) from the EV1 distribution using the parameters listed in Table 2.

Return Period y	Sumner Head	Bridge St	Ferrymead	Styx
2	10.764	10.682	10.641	10.756
5	10.868	10.804	10.741	10.900
10	10.937	10.885	10.807	10.996
20	11.003	10.963	10.870	11.088
50	11.089	11.063	10.952	11.206
100	11.153	11.139	11.014	11.296
200	11.217	11.214	11.075	11.384
500	11.302	11.313	11.156	11.501
1000	11.365	11.388	11.217	11.590

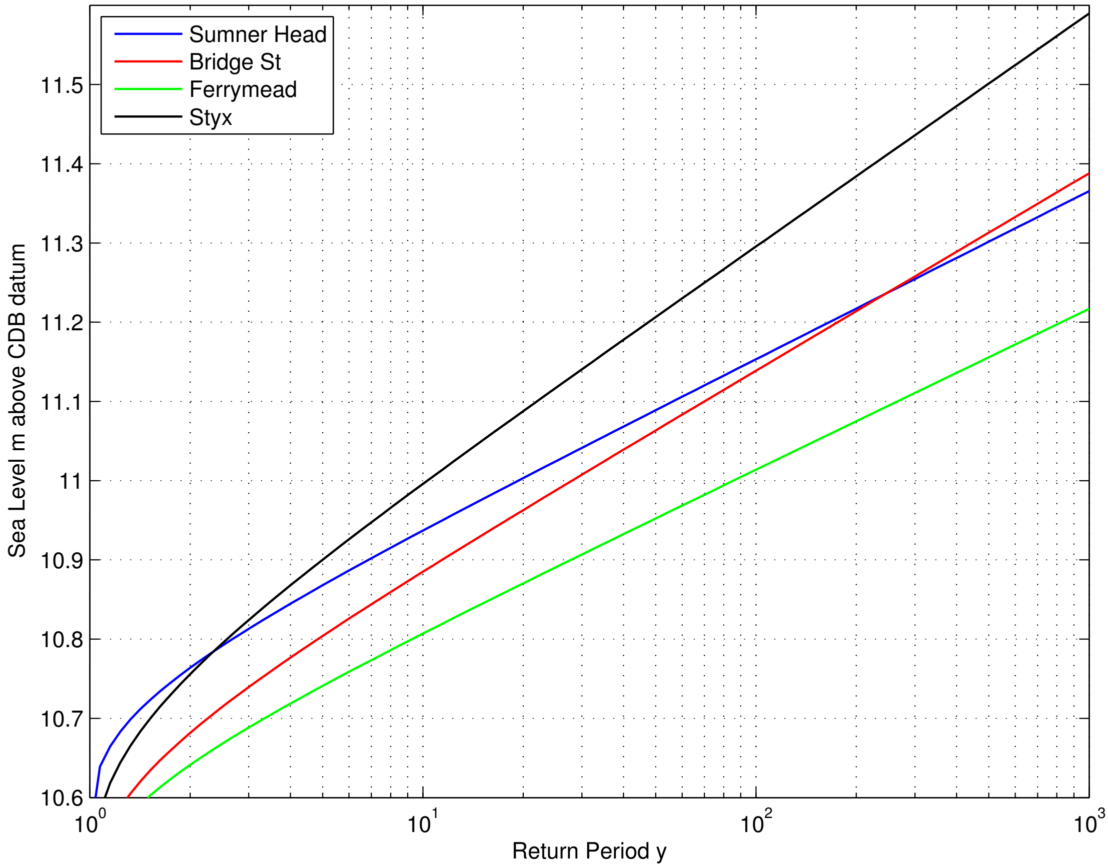

Figure 2. EV1 distributions for all sites for the parameters listed in Table 2.

To assess the validity of the extrapolated distributions in Table 3 and Figure 2, the 1000-y return period levels are compared with HAT[5] for each site in Table 4. The difference between these levels is an indication of the storm surge that would be needed when the tide was HAT for the 1000-y return period levels to occur. In the companion study, Goring 2018[3], storm surges up to 0.55 m were found, so the required storm surge of 0.569 m at Sumner Head is perfectly reasonable. However, for the higher levels at the estuary sites to be achieved there would need to be substantial wind set-up across the estuary.

Table 4. Comparison of 1000-y return period levels with highest astronomical tide (HAT).

	Sumner Head	Bridge St	Ferrymead	Styx
1000-y RP	11.365	11.388	11.217	11.590
HAT	10.796	10.434	10.441	10.657
Difference	0.569	0.954	0.776	0.933

5 HAT is highest astronomical tide, being the highest high tide in a tidal epoch of 18.6 years.

4. Summary and Conclusions

Storm-tide levels (the levels at high tide) have been extracted from the records for Sumner Head on the open coast and for Bridge St and Ferrymead in the Avon-Heathcote/Ihutai Estuary, and Styx in Brooklands Lagoon.

Annual maxima have been extracted from the records and these have been subjected to statistical tests to assess their independence. The estuary sites were found to be independent, but Sumner Head shows a slight upward trend.

The EV1 distribution was fitted to the annual maxima using probability weighted moments.

The event of 02-Feb-2018 had the highest storm tide levels for all sites; and for the estuary sites, the event of 21-Jul-2017 was second highest.

Using the fitted distributions, the levels for various return periods were calculated, with extrapolations up to 1,000 years.

The validity of the 1,000-year extrapolations was assessed by comparison with HAT[5], showing that for Sumner Head the extrapolation is reasonable, but for the estuary sites, it is somewhat higher than would be expected and would need substantial wind set-up across the estuary to be achieved.

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Appendix I: EV1 Distribution

The theoretical EV1 distribution may be obtained from the parameters by first calculating the cumulative probability, *P*, from the return period, *R:*

$$P = 1 - 1/R \tag{1}$$

The corresponding level is given by:

$$y = \mu - \sigma \log(-\log(P)) \tag{2}$$

where the location and scale parameters are listed in Table 2.

Conversely, the return period may be calculated for a specific level, *y*, by first calculating the cumulative probability:

$$P = \exp(-\exp(-(y - \mu)/\sigma)) \tag{4}$$

then the return period:

$$R = \frac{1}{(1 - P)} \tag{5}$$

22-Jul-2018

Storm Tide at Sumner Head

1. Introduction

This technical note describes the process involved in establishing a sequence of storm tide levels at Sumner Head. Storm tide is defined as the maximum sea level that occurs at each high tide. It includes the astronomical tide, storm surge, and long-period contributions such as El Nino/Southern Oscillation effects and sea-level rise. There is debate as to whether it should also include short-period waves such as Pegasus Bay seiche (3.4 h periods) and far infra gravity (FIG) waves (2 to 20 min periods). In this study two datasets were produced:

1. Storm tide using 1-min data – includes Pegasus Bay seiche and FIG waves;
2. Storm tide using 15-min means – includes Pegasus Bay seiche, but **not** FIG waves.

2. Data

The data used in the study are listed in Table 1. All data were at 1-min intervals.

Site	Agency	Start	Finish	Long-Term Mean
Sumner Head	NIWA	03-Jun-1994	04-Apr-2018	9.170 m above CDB datum
SUMT	GeoNet	11-Aug-2010	04-Apr-2018	1.925 m above instrument zero
Lyttelton	LPC	01-Jan-1998	04-Apr-2018	1.411 m above CD

The Sumner Head data were from the updated dataset reported on by Robinson & Bell (2018)[1]. Their updating involved adjustments for datum shifts and errors in the data from 2010 to 2018. In this report we extend those corrections back to 1998 using the Lyttelton tide gauge. We also fill gaps in the record where possible using either SUMT or Lyttelton.

The SUMT data were derived as 1-min means of 1 Hz data from GeoNet's LTH database. These data were used in preference to the 1-min data available at the GeoNet ftp site because those data have been low-pass filtered in a way that eliminates waves with periods less than 10 min. Taking 1-min means of 1 Hz data produces that have the same characteristics as a standard tide gauge (like Sumner Head and Lyttelton).

For SUMT and Lyttelton, the data were transformed to CDB datum by adding 7.245 m and 7.659 m respectively.

3. Methods

For each site, the times of high tide were hindcast for the period of record, then for each high tide the following steps were undertaken:

1. Retrieve a window of 1-min data for 2 hours either side of high tide;
2. Find the time and level of the maximum within the window;
3. If the time is within the boundaries of the window, accept this high tide, otherwise reject it;

1 Robinson, B.; Bell, RG. 2018: NIWA Letter Report: Comparing the NIWA and GeoNet/LINZ Sumner sea level gauges.

4. Calculate 15-min means for the 4 h of data over high tide and repeat steps 2 and 3.

3.1 FIG Effect

The effect of including FIG waves in the estimation of storm tide is illustrated in Figure 1 which shows for SUMT the 1-min data with 15-min means over-plotted. For this case, the difference in level between the maxima is 0.277 m.

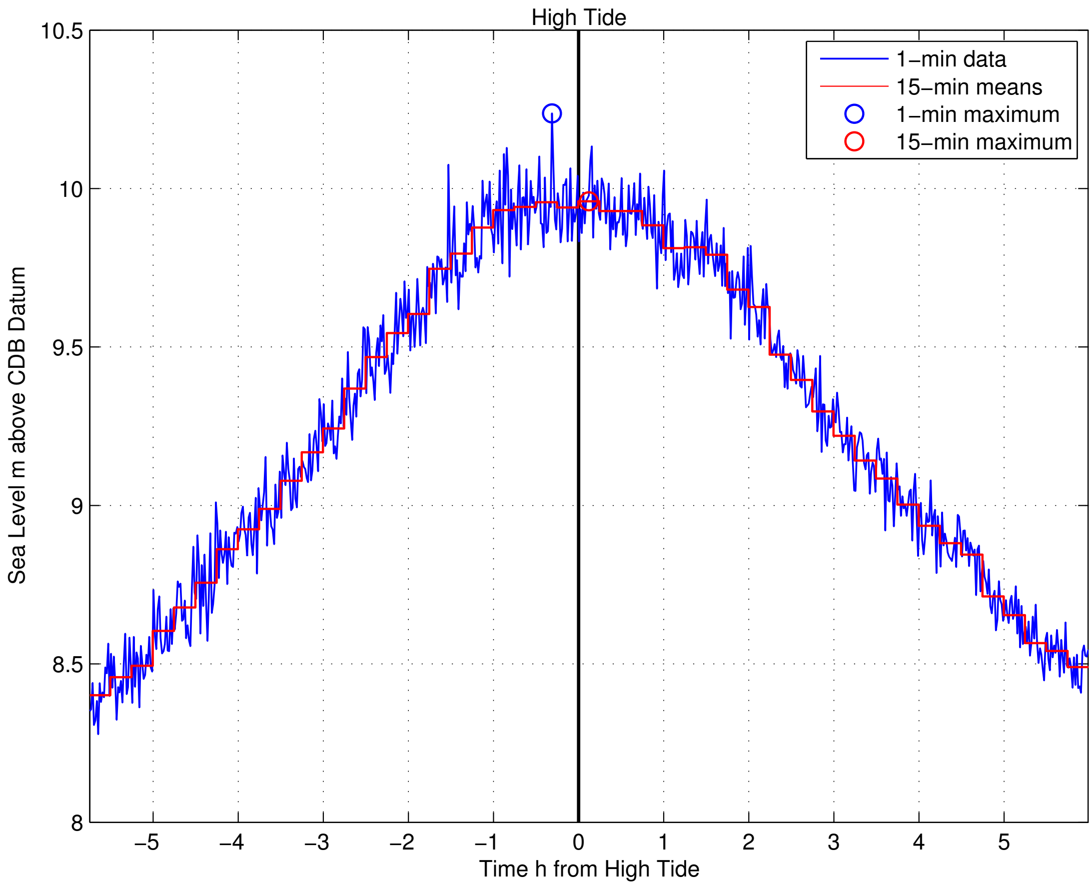

Figure 1. Comparison of raw 1-min data (blue) and 15-min means (red), with the maximum levels marked with circles.

The difference in maxima shown in Figure 1 is larger than normal, as indicated in Table 2 which is for the entire dataset at each location. Nevertheless, these differences make comparison between the data cloudy, so for corroborative analysis 15-min means have been used.

Table 2. Statistics of the difference in maxima from 1-min data and 15-min means in mm.

Statistic	Sumner Head	SUMT	Lyttelton
Mean	25	45	26
Std Dev	22	29	16
2.5%	4	15	7
50%	19	37	22
97.5%	85	126	65

4. Results

4.1 Storm Tides at the Different Sites

Figure 2 shows the storm tides at all three sites for a typical month of record over a perigean spring tide. The points are discrete, of course, but for clarity they have been joined, which shows the gap in the Lyttelton record between 28-Feb and 3-Mar. The figure shows that Sumner Head and SUMT are generally coincident, but Lyttelton is somewhat different, and this is typical of the entire overlapping record. Indeed, the statistics of the differences presented in Table 3 confirm this.

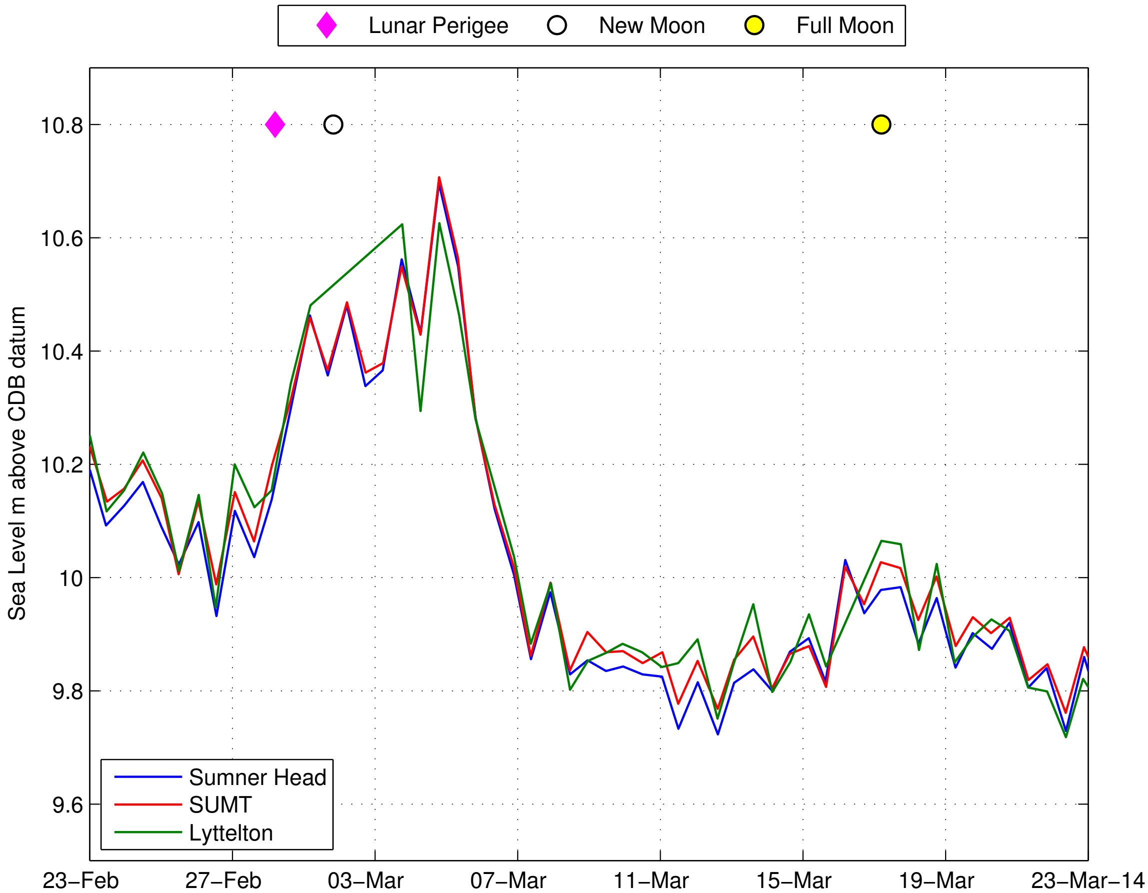

Figure 2. Typical month of record over a perigean spring tide.

Table 3. Statistics of the difference in storm tide levels from Sumner Head in mm.

Statistic	**Sumner Head - SUMT**		**Sumner Head - Lyttelton**	
	All	**> 10.4 m**	**All**	**> 10.4 m**
No. High Tides	4,912	194	13,321	366
Mean	-0.001	-0.017	0.063	0.001
Std Dev	0.064	0.057	0.107	0.111
2.5%	-0.135	-0.208	-0.135	-0.181
50%	-0.006	-0.011	0.059	-0.018
97.5%	0.152	0.083	0.304	0.301

Two sets of statistics are presented in Table 3. One set is for all the storm tides in the record and the other set is for those storm tides that exceed 10.4 m above CDB datum. On average, for all storm tides, Sumner Head and SUMT are the same, but there are departures, both positive and negative. For storm tides above 10.4 m, SUMT is slightly higher on average. For Lyttelton, for all storm tides, Sumner Head is higher, but for storm tides above 10.4 , they are on average about the same.

The SUMT gauge is a submerged pressure transducer. Such instruments are notorious for drifting and are generally not used for long-term tide gauges. Indeed, the gauge is for tsunami measurements, whose oscillations last for a few hours and where day-to-day drift is irrelevant.

The Lyttelton tide gauge is in Lyttelton Harbour, some distance from Sumner Head, so we can expect there to be differences because of harbour effects. It is an ultra sonic gauge gauge that is not subject to drift.

4.2 Adjusting the Levels

Table 3 shows the overall statistics of the differences between Sumner Head and the other gauges, indicating that for most events the level at Sumner Head is about the same as SUMT and Lyttelton. However, there are occasions when the Sumner Head level is less than that at the other gauges and we need to consider whether the level for those events needs to be adjusted upwards to match the other gauges.

Examination of the record when both SUMT and Lyttelton data are available (i.e., Aug-2010 onwards) revealed that there were 7 storm tides for storm tide levels greater than 10.4 m when SUMT exceeded Sumner Head by more than 0.1 m. Those events are listed in Table 4 along with a suggested adjustment that needs to be made to the Sumner Head record.

Table 4. Events when SUMT exceeds Sumner Head by 0.1 m or more for storm tides greater than 10.4 m.

Time	Sumner Head	Difference	Adjusted Level
13-Aug-2010 06:38	10.199	-0.217	10.416
13-Aug-2010 19:08	10.195	-0.317	10.512
28-Dec-2010 09:53	10.275	-0.240	10.515
07-Jul-2011 21:53	10.248	-0.186	10.434
18-Oct-2012 06:08	10.305	-0.147	10.452
28-Apr-2017 18:23	10.296	-0.177	10.473

The effect of the adjustments is illustrated in Figure 3, which is for the first two in Table 4. The other adjustments are similar.

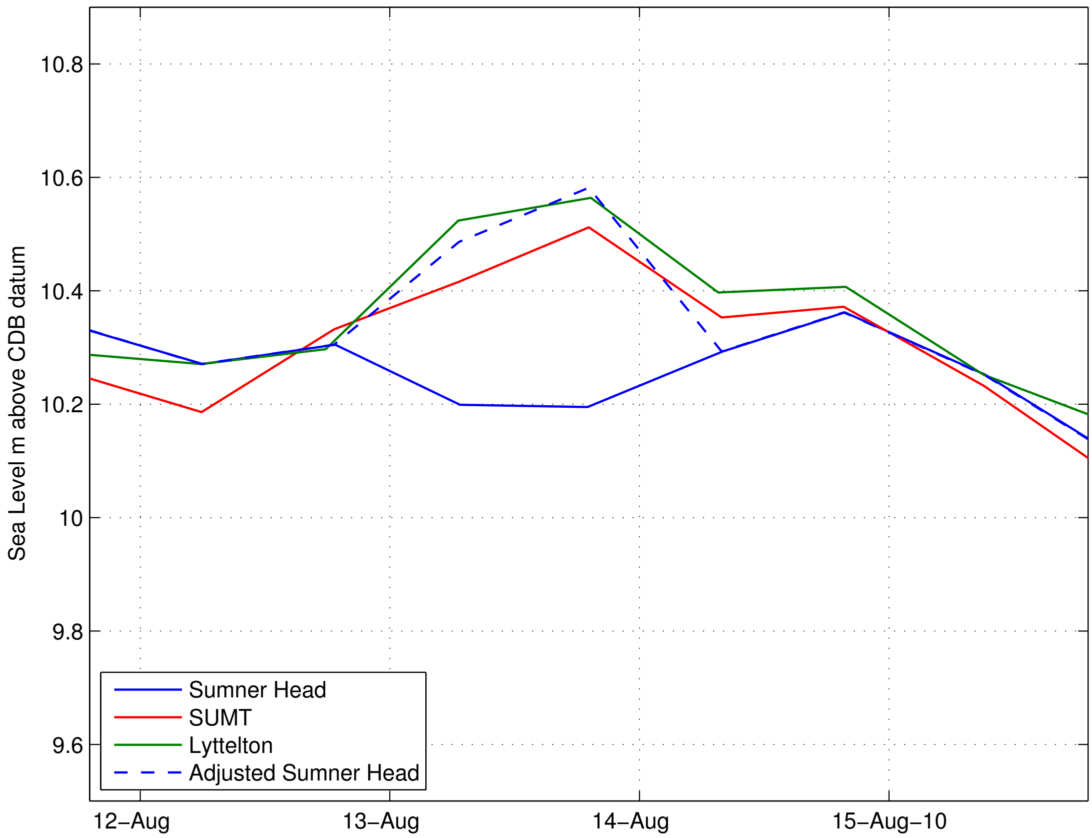

Figure 3. Typical adjustment in the levels at Sumner Head to align with SUMT.

The exercise was repeated for the period from Jan-1998 to Aug-2010 when data from Lyttelton were available, where 15 events emerged where the difference from Sumner Head exceeded 0.1 m. However, there is considerable doubt as to which record is correct, as shown for one of the events in Figure 4. Therefore, the events were inspected manually and only those where there are obvious errors at Sumner Head were replaced. This amounted to the three events listed in Table 5.

Table 5. Events when Lyttelton exceeds Sumner Head by 0.1 m or more for storm tides greater than 10.4 m.

Time	Sumner Head	Difference	Adjusted Level
04-Jan-2002 09:05	10.085	-0.385	10.470
23-Dec-2003 16:35	10.250	-0.172	10.422
28-Feb-2010 14:50	10.202	-0.367	10.569

However, on further inspection it was discovered that the 28-Feb-2010 event was actually the Chile tsunami, where the response at Sumner Head and in Lyttelton Harbour were quite different. Therefore, adjusting the Sumner Head record for this event is inappropriate.

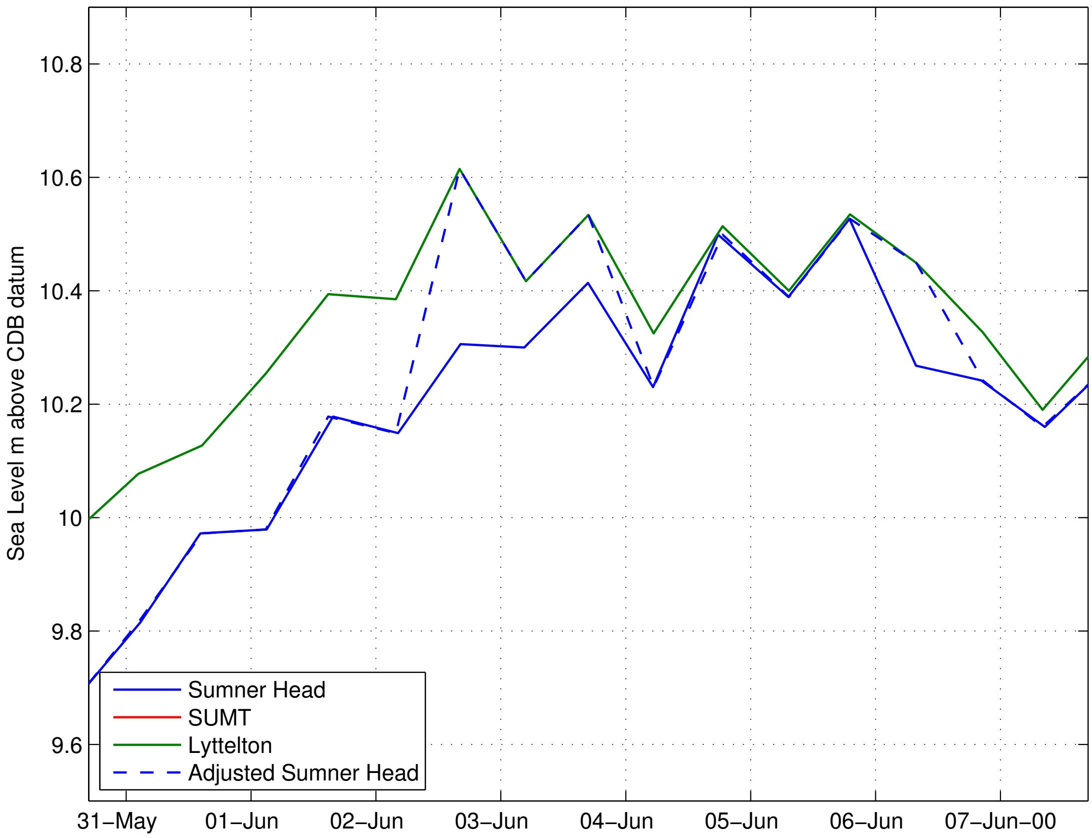

Figure 4. Comparison between Sumner Head and Lyttelton where there is doubt about which record is correct.

4.3 Filling the Gaps

Out of the 16,823 storm tides in the period from 1994 to 2018 of the Sumner Head record, 514 are missing from the dataset for one reason or another, including 242 for the period from 10-Jan to 15-May-2013 when the recorder was down.

For the period from 11-Aug-2010 onwards when SUMT data are available, the gaps were filled with SUMT.

For the period from 1-Jan-1998 to 11-Aug-2010 when Lyttelton data were available, but SUMT were not, the gaps were filled with Lyttelton data.

In summary, of the 514 gaps, 331 were filled with data from SUMT and 67 were filled with data from Lyttelton, leaving 116 unfilled gaps.

4.4 Re-Inserting the FIG Waves

The analysis has been carried out on 15-min means, i.e., with FIG waves eliminated. For the final time series, the FIG waves need to be re-introduced. To do this, the difference between the raw signal (1-min intervals) and 15-min means is calculated for 1 h either side of high tide and the value that is exceeded 2.5% of the time is calculated. This is the correction for FIG waves that is added to the storm tide.

5. Summary and Conclusions

Comparison of the original Sumner Head record and the record enhanced with adjustments (Section 4.2) and gaps filled (Section 4.3), indicates that there was only one change in position for the highest 100 levels (at position 30).

Thus, the conclusion is that the original record of storm tides at Sumner Head is adequate for the purpose of estimating extreme values.

For the analysis of storm tides + FIG waves, the storm tides have been enhanced by adding the FIG amplitude that is exceeded by 2.5% of data for an hour either side of high tide. On average, this increases the storm tide heights by 0.080 m.

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