Impacts of Climate Change on Urban Infrastructure & the Built Environment

A Toolbox

Tool 2.2.3: Guidance on assessing extreme sea level in New Zealand

Author

S. Stephens[1]

Affiliation

1. NIWA, PO Box 11115, Hamilton

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1. Methods for assessing the probabilities of extreme still water levels

1.1 Introduction

The aim of an extreme sea-level analysis is to determine the height and likelihood of occurrence of unusually high (or low) sea levels. In particular, extreme sea-level analyses usually require estimation of the probability of sea levels that are more extreme than any that have already been observed.

This tool aims to provide enough background to extreme sea-level analysis that the reader can:

- Understand how an extreme sea-level analysis works.
- Select an appropriate method to analyse available data.
- Understand the advantages and disadvantages of various extreme sea-level analysis methods.
- Interpret the output of an extreme sea-level analysis.

1.2 Extreme sea-level analysis techniques

Table 1.1 shows extreme value techniques commonly applied to sea-level data. The range of methods in Table 1.1 provides sufficient flexibility to work with most sea-level records likely to be encountered. These techniques can be applied to stationary[1] sea-level sequences, but have also been applied to datasets including temporal trends such as from sea-level rise or El-Nino Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO) climate variability, and in more advanced analyses such as spatially and temporally correlated analyses.

Each of the methods in Table 1.1 has advantages and disadvantages, which relate to ease of use and to accuracy (bias) and uncertainty (variance). Generally, the methods that make use of more of the available sea-level measurements are most accurate and have the least uncertainty – they make more “efficient” use of the data and are preferred where accuracy is important. Techniques that use less data are easier to

[1] A data timeseries is stationary if it has random variability, but the mean and variance of that random variability remains unchanged with time. Thus a sea-level record is not stationary if it includes long-term sea-level rise.

apply and are preferred where a low-effort or approximate analysis is required, and/or where long records are available.

Extreme sea-level analyses are based on extrapolation from past sea-level measurements. The quality, frequency and length of the sea-level record control the accuracy and uncertainty of the extreme sea-level analysis and can govern the choice of extreme sea-level method. Each extreme sea-level method has unique data requirements; for example, the *Annual Maxima Method* (*AMM*) requires observed annual maximum sea levels, whereas the *Empirical Simulation Technique* (*EST*) requires a high-quality digital dataset sampled at least hourly. Extreme sea-level analyses are sensitive to outliers (erroneous measurements). Data preparation is extremely important, and the most time-consuming component of an extreme sea-level analysis. Raw sea-level records are seldom perfect and can be affected by siltation of the recorder, timing errors (e.g., daylight saving), datum shifts and gaps in the record, for example. Sea-level measurements must be quality assured before use in an extreme sea-level analysis. No analysis technique can make up for poor data.

Table 1.1: Summary of extreme value techniques for estimating the probabilities of extreme still water levels.

		Advantages	Disadvantages
Simple to apply, less effort for data quality check , lower data efficiency (more data wastage), longer data records required, lower confidence (higher uncertainty) for given record duration.	*Direct* methods	***Annual Maxima Method (AMM)***	
		• Simple to apply (no thresholds) with easily-obtained software. • Simple data treatment and post-processing (Annual Maxima easily obtained and quality checked). • Annual Maxima records sometimes extend beyond the modern continuous digital records.	• Inefficient use of data (wastage). About 40-years of Annual Maxima required for 100-year ARI estimate. • Long sea-level record required, 10-years minimum, 50-years preferable (large uncertainty for short records). In some locations this is partially compensated by Annual Maxima records that extend beyond modern digital records.
		r-largest method (RLM)	
		• Extension of *AMM*; commonly applied with easily-obtained software. • Better data use efficiency than *AMM* (higher confidence – lower uncertainty). • Sometimes used in more advanced spatially- and temporally-extended analyses because threshold is less site and time dependent than for *POT*.	• Data efficiency is low (wastage high) compared to *POT* and *JPM–EST*. About 25-years data required for 100-year ARI estimate. • Choice of number of events per year *r* is subjective – some user experience preferred. • Long sea-level record required, 10-years minimum.
Use more of the available data (higher efficiency), more accurate results for short records, higher confidence (lower uncertainty), more complex to apply, more effort required to check data quality.		***Peaks-over-threshold method (POT)***	
		• Most efficient data use of the *direct* methods (highest confidence, lowest uncertainty). • Commonly applied with easily-obtained software.	• Requires subjective choice of threshold – user experience, or trial and error. • At least 10-years of data required for 100-year ARI estimate. • Use of more data requires more stringent data quality check.
	Indirect methods	*Revised joint probability (RJPM)* and ***Empirical* Simulation Technique *EST***	
		• Most efficient use of data. • Suitable for short records (< 5-years). • Higher confidence (lower uncertainty).	• Sensitive to data errors, requires stringent data quality assurance. • Complex and time-consuming to apply – requires high level of user experience relative to *direct* methods. • Less commonly applied and available software. • Assumes tide and storm surge are independent, which may not be true in estuaries.

The results of an extreme value analysis depend on the sampling frequency and duration of the underlying data, because these factors influence the sea-level processes that are included. For example, high-frequency data (e.g., 1, 5 or 10 minute sampling) may include short-term fluctuations due to waves or seiche, whose inclusion can raise extreme sea-level estimates. Modern sea-level gauges commonly measure as frequently as every minute, which is useful for identifying short period processes such as seiche in ports and harbours. For extreme sea-level analysis it is common to subsample the data to ½-hour or 1-hour intervals, which is sufficient to resolve the processes contributing to the storm tide[2] while avoiding the contribution of waves and seiche.

There are two commonly used types of extreme sea-level analyses: *direct* and *indirect* methods.

1.2.1 Direct methods

Direct methods are so called because they "directly" analyse the *observed/measured* sea level maxima that occur during storm tides. The measured storm-tide maxima "directly" include all the components of sea-level that can occasionally combine to produce unusually high sea levels, such as mean level of the sea (MLOS), spring tide, and storm surge. *Direct* methods use techniques based on *extreme value theory*, which in simple terms involves fitting an "extreme-value model" to the most extreme sea-level maxima in the record (subject to appropriate data sampling). An underlying principle is that the extreme values are stochastic (random) in nature. The "extreme-value model" is then used to predict the height and frequency of occurrence of extreme sea levels. Direct methods listed in Table 1.1 are the *Annual Maxima Method* (*AMM*), the *r-largest* method (*RLM*), and the *peaks-over-threshold* (*POT*) method. Coles (2001) gives a simple and thorough introduction to the *direct* techniques, with associated computer code for their use, and there are many other commercial software packages available for the *direct* techniques in Table 1.1 (Stephenson and Gilleland 2006). There are certain limitations that come with the adoption of extreme value theory:

1. The results might be inaccurate when applied to short sea-level records.

2. The models themselves are developed under idealised circumstances, which may not be exact (or even reasonable) for a process under study. For example, *direct* methods analyse the *observed* extremes of sea level, which in New Zealand are usually a coincidence of a moderate to high storm surge and a high spring tide. Extreme value theory is a valid approach for modelling the

[2] see Tool 2.2.2 for definition of "storm tide" and other drivers of sea-level variability.

storm surge component of sea level because it is an approximately stochastic process. However, the tide, which makes up most of the sea-level variance, is deterministic, and so the *direct* application of extreme value theory is violated.

3. The models may lead to wastage of information when implemented in practise. (Coles 2001).

The above limitations imply that extreme value theory is best applied *directly* to sea levels when long records (sea level measured over many decades) are available, and when the stochastic storm surge component is relatively large in comparison to the tidal component. These limitations do not mean that *direct* methods cannot and should not be used for modelling extreme sea levels, they are widely applied, but the practitioner should be aware of the limitations and associated uncertainty when interpreting the results. Haigh et al. (2010) showed that *direct* methods using extreme value theory underestimate the long (> 20 years) period return levels when the astronomical tidal variations of sea level (relative to a mean of zero) are about twice that of the non-tidal variations. This is the case in New Zealand.

In the *AMM* the generalized extreme value (GEV) distribution is fitted to the sea-level annual maxima. Note that in the *AMM* the maxima have been chosen from a "block size" equal to 1 year. Maxima can be selected from other block sizes (e.g., monthly, or seasonally), but a 1-year block removes seasonal influences from the analysis. From a practical perspective extraction of the annual maxima is relatively easy to do, and only a few dozen (for a relatively long record in New Zealand terms) annual maxima need be carefully checked for accuracy, making this method popular despite its relatively inefficient use of data (Table 1.1). The sea levels (return levels) corresponding to chosen Average Recurrence Intervals (ARI) are obtained from the fitted GEV distribution.

The *RLM* is an extension of the *AMM*, but instead of fitting the GEV distribution to annual maxima, it is fitted to the *r* largest sea levels within the year, for small values of *r*. This leads to more efficient use of the data compared with the *AMM*. The *r* sea levels must be independent of each other, e.g., separate storms or separate spring tide period. The choice of *r* is analogous to the choice of block size (chosen as 1 year in the *AMM*), implying a balance between bias and variance. In this case, setting *r* too high is likely to include too many non-extreme values, violating the asymptotic basis for the model and leading to bias (inaccuracy); setting *r* too low will generate few excesses with which the model can be estimated, leading to high variance (uncertainty) with no real advantage over the *AMM*. The standard practice is to adopt as high an *r* as possible, subject to the limit model providing a reasonable approximation (Coles 2001). A typical value for *r* is about 5 maxima per year.

Modelling only block maxima is a wasteful approach to extreme value analysis if other data on extremes are available. If an entire timeseries of say, hourly or daily observations is available, then better use is made of the data selecting all values over some high threshold, known as the peaks-over-threshold method (*POT*), and fitting the Generalised Pareto Distribution (GPD) to the threshold excesses. The *POT* approach contrasts with the block maxima approach through the characterisation of an observation as extreme if it exceeds a high threshold. But the issue of threshold choice is analogous to the choice of block size in the block maxima approach, implying a balance between bias and variance. The standard practice is to adopt as low a threshold as possible, subject to the limit model providing a reasonable approximation. (Van den Brink et al. 2005) suggest that to avoid bias, the *POT* method should be employed with threshold of at most 4 storm tides per year.

1.2.2 Indirect methods

Indirect methods are so called because they involve splitting the sea level into its deterministic (predictable) tidal and stochastic (e.g., unpredictable, storm-driven) non-tidal components, and analysing the two components separately before recombining. *Indirect* methods are more complicated and require stringent data quality control, but make more efficient use of the available data and so give better results for short data records. The *indirect* methods also overcome the main theoretical limitations of extreme value theory application to sea levels, and return sea levels can be estimated from relatively short records (<5 years) because all storm surge events are taken into account, not just those that lead to extreme levels. The revised joint probability method (*RJPM*) (Pugh and Vassie 1978; Pugh and Vassie 1980; Tawn and Vassie 1989) is a widely-applied *indirect* method, and the newly-developed empirical simulation technique (*EST*) is being applied in New Zealand (Goring et al. 2010). An advantage of the *EST* relative to the *RJPM* is that it gives robust confidence intervals, and incorporates additional sea-level components such as MLOS. A disadvantage of the *indirect* methods is that the practitioner must develop the computer code themselves; NIWA has working versions of both the *RJPM* and *EST*.

1.3 Integrating extreme sea levels and sea-level rise

From sea-level data it may be necessary to obtain an estimate of the maximum sea level likely to occur in the next 100 or 1000 years. How can we estimate what levels may occur in the next 1000 years without knowing what climate change and sea-level rise might occur? Although the pattern of sea-level variation may not appear to have changed in the last 50 years of measurement record, such stability may not persist in the future. The “1000-year return level” is only meaningful under the assumption of stability (or stationarity) in the prevailing process.

About 50-years of data is required for robust estimates of century scale trends in mean sea level. This is because of the effects of El Niño–Southern Oscillation (ENSO) at 2- to 5-year cycles and of a phenomenon called the Interdecadal Pacific Oscillation (IPO) operating across the Pacific at 20- to 30-year cycles. Unfortunately, these long, but erratic, cycles in sea level mask the underlying trend called sea-level rise.

Extreme-value theory (*direct* methods) is strictly not applicable to non-stationary processes that have characteristics that change systematically through time e.g., seasonal effects, or in the form of trends, possible due to long-term climate trends. Most open-coast sea-level records in New Zealand are 7–18 years long (at time of writing in 2010), which is insufficient to resolve long-term mean sea-level trends[3].

For short records (< 30 years), ignoring the long term sea-level rise trend will make little practical difference to the extreme value predictions relative to the present day. For short records a *direct* extreme value analysis can be made by assuming stationarity (no sea-level rise trend) and an allowance for sea-level rise can be subsequently added to the extreme value predictions. Techniques are available to build sea-level rise or ENSO/IPO variability into *direct* extreme value analyses if desired (Coles 2001).

It is possible for a short-duration sea-level record to coincide with a period with unusually high (low) sea levels because of short (ENSO) or medium (IPO) term climate variability causing higher (lower) MLOS or more (less) intense storm surges. It has been shown that *indirect* methods (*RJPM*, *EST*) are less affected by climate variability than the *direct* methods (*AMM*, *RLM*, *POT*) because the *indirect* methods allow for combinations of high storm surge and high tide that may not actually occur during a short measurement period (e.g., Goring et al. 2010). The *direct* methods are limited by the frequency of occurrence of high storm tides during the measurement period.

1.4 Reporting and plotting extreme sea levels

Extreme sea-level analysis assigns a likelihood of occurrence to unusually high sea levels. It has been common to report these likelihoods in terms of "return periods", for example a "sea level with a 100-year return period", or a "1 in 100-year sea level". While the use of "return period" is a generally accepted description of extreme value likelihood, it can lead to the misconception that such an event only occurs every "100 years" for example, when in fact such high sea levels can occur more or less frequently. The term "Average Recurrence Interval" (ARI) has the same meaning as "return period" but is more descriptive and so is preferable to the term "return period". For example a 100-year ARI (100-year return period) sea level is "the sea level that is

[3] See Tool 2.2.1 for guidance on assessing long-term sea-level rise.

equalled or exceeded once, *on average*, every 100 years". The occurrence likelihood of extreme sea levels can also be expressed as an Annual Exceedance Probability (AEP). The AEP directly expresses the extreme sea level in terms of a probability/likelihood. For example, the 100-year ARI sea level (or 1 in 100-year return period sea level) has an AEP of 0.01. In other words, the probability of such a high sea level occurring in any one year is low (only 0.01, or 1%), but there is still a chance that such an event could occur any time. The formula for converting between ARI and AEP is $AEP = 1 – \exp(–1/ARI)$, which simplifies to $AEP \approx 1/ARI$ for longer ARI (> 30 years).

Extreme sea-level analyses can be presented in tables (e.g., Table 1.2), or are commonly plotted as in Figure 1.1.

Figure 1.1 and Table 1.2 show results of extreme sea-level analyses undertaken using two *direct* (*AMM* and *POT*) and one *indirect* (*EST*) technique, based on hourly sea levels measured at Sumner Head between June 1994 and July 2009. For the *AMM* and *POT* analyses, the solid lines mark the central estimate while the dashed lines mark the 0.05 confidence intervals for the fits. The empirical simulation technique (*EST*) results are plotted in blue and the error bars show the range of 100 estimates at each annual exceedance probability (AEP). In this example the three techniques have similar central estimates, but the uncertainty associated with the techniques varies markedly according to the amount of data used by each technique. Thus for the *AMM* we are confident (to the 0.05 confidence interval) that the sea level with annual exceedance probability of 0.01 will fall between 1.65–2.18 m. For the *EST* we are confident (to the 0.05 confidence interval) that the sea level with annual exceedance probability of 0.01 is between 1.86–1.89 m, a much tighter confidence interval.

The extreme sea-level curves in Figure 1.1 begin to flatten out at lower AEP (higher ARI). This is typical of environmental data where physical processes limit the maximum possible values. The various components of sea-level variability are physically limited. For example, tides are limited to highest astronomic tide, storm surge is limited by the physical capacity of weather systems (combinations of low barometric pressure, strong winds and speed and track of movement) and their interaction with the local bathymetry.

Figure 1.1 also shows the value of including confidence intervals for the extreme value analyses. Although the central estimates for the three methods are all similar in this example, we are much less confident in the *AMM* results than the *EST*. Thus, while the *AMM* is easily applied, its error limits should be carefully considered when applying it to sea-level records shorter than about 30-years. The confidence intervals can be used to allow for risk when planning development. For example, a low-cost development (e.g., a beach toilet block) with a short planning timeframe might use the central estimate as a design sea level. A high-cost development (e.g., commercial real-estate) with longer planning timeframe should use the upper confidence limit – that way the design sea level is less likely to occur. In addition to extreme sea-level analysis, allowance for sea-level rise is required for longer planning timeframes [see Figure 1.1 of Tool 2.2.1].

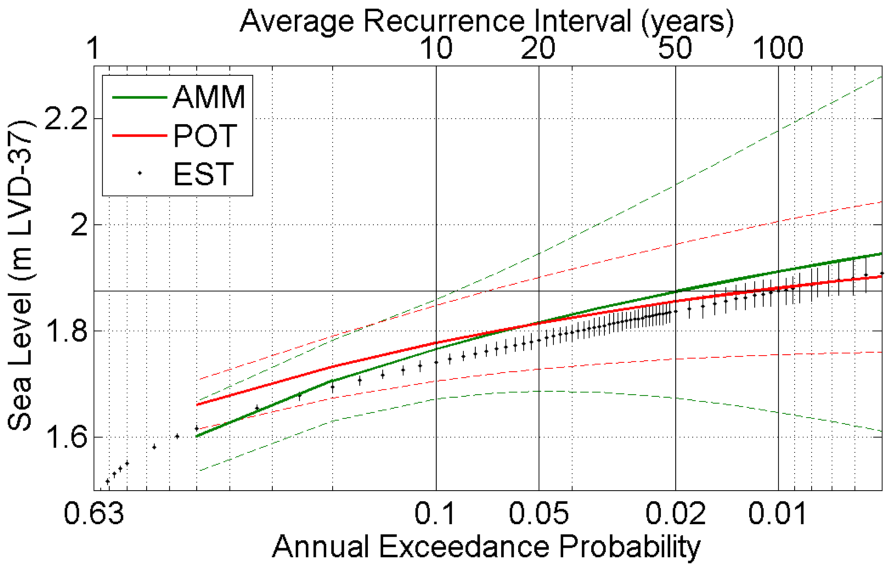

Figure 1.1: Comparison of *AMM*, *POT* and *EST* extreme value estimates of Sumner Head sea levels.

Table 1.2: Comparison of *AMM*, *POT* and *EST* extreme value estimates of Sumner Head sea levels. The central estimates and the *upper* and *lower* 0.05 confidence interval estimates are specified for each method.

AEP	ARI	*AMM* central	*AMM* lower	*AMM* upper	*POT* central	*POT* lower	*POT* upper	*EST* central	*EST* lower	*EST* upper
0.39	2	1.60	1.53	1.67	1.66	1.61	1.71	1.62	1.61	1.62
0.18	5	1.71	1.63	1.78	1.73	1.67	1.79	1.69	1.69	1.70
0.10	10	1.77	1.67	1.86	1.78	1.71	1.85	1.74	1.73	1.75
0.02	50	1.87	1.67	2.07	1.86	1.75	1.96	1.84	1.82	1.85
0.01	100	1.91	1.65	2.18	1.88	1.76	2.01	1.87	1.85	1.90
0.005	200	1.95	1.61	2.28	1.90	1.76	2.04	1.91	1.87	1.94

1.5 Rate the likelihood of a specific sea level occurring

Likelihood can be expressed either numerically as a percentage chance of an event occurring or described qualitatively from “almost certain” to “rare”. For instance, “almost certain” could mean that something has happened before and is expected to happen again in the next 12 months. “Rare” could mean although something has not happened before in our experience, it is in the realms of possibility (King 2010).

The numerical likelihood of the probability of an extreme sea level occurring within the design life of an asset being considered can be determined using Table 1.3. That number can then be used to determine a qualitative rating to express the likelihood of that sea level occurring. Table 1.4 provides an example of likelihood ranges that could be used (King 2010).

Likelihood should be assessed in terms of the design life of the asset or infrastructure that is at risk from high sea level. For example some buildings might more realistically have a 100-year lifespan, even though they are only required to be designed for a 50-year lifespan. Therefore, the probability that a damaging sea level will occur within that longer 100-year time horizon should be considered. The risk to a subdivision should be analysed over a longer period of time, because once land has been developed for residential use it is more than likely to remain occupied for very long periods of time, if not permanently. For temporary assets (e.g., a culvert) or temporary land uses (e.g., a camping ground), a shorter time horizon may be appropriate (King 2010).

To illustrate this process in action consider a sea level that might occur once, on average, every 100 years (a 100-year ARI event) and an asset that has a design life of 100 years. Using the two tables below, the numerical likelihood from Table 1.3 would be 63% and it would be considered as ‘likely’ to occur. Keep in mind that a “1-in-100” year event means that there is a 1% chance of the event occurring in a single year, not that the event only occurs once every 100 years (King 2010).

Table 1.3: Likelihood of high sea level occurring within a given time horizon (Adapted from King, 2010). The probability *P* that a specific sea level will be equalled or exceeded in height, during any design lifetime L_D can be calculated using $P = 1 - [1 - (1/ARI)]^{L_D}$.

ARI (years)	Design lifetime horizon (years) L_D						
	2	5	10	50	75	100	200
2	75%	97%	100%	100%	100%	100%	100%
5	36%	67%	89%	100%	100%	100%	100%
10	19%	41%	65%	99%	100%	100%	100%
50	4%	10%	18%	64%	78%	87%	98%
75	3%	6%	13%	49%	63%	74%	93%
100	2%	5%	10%	39%	53%	63%	87%
200	1%	2%	5%	22%	31%	39%	63%

Table 1.4: Sea-level likelihood ratings (Adapted from King, 2010).

Rating	Percentage chance that a sea level with a given average recurrence interval will occur within the design life
Almost certain	> 85%
Likely	60% – 84%
Possible	36% – 59%
Unlikely	16% – 35 %
Rare	< 15%

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