PROBABILISTIC HAZARD ASSESSMENT METHODOLOGY TO SUPPORT LOCAL ADAPTATION PLANNING IN LAKE MACQUARIE

D Wainwright[1,2,3], D Callaghan[3], A Howe[4], D Hanslow[5],
[1]Salients Pty Ltd, Wallsend, NSW
[2]University of Newcastle, School of Environmental and Life Sciences (Conjoint Lecturer)
[3]University of Queensland, School of Civil Engineering
[4]Lake Macquarie City Council, Speers Point, NSW
[5]NSW Office of Environment and Heritage, Newcastle, NSW

Abstract

The suburbs of Pelican, Blacksmiths and Swansea adjoin the entrance channel to Lake Macquarie and are subject to flooding from catchment-derived events and periodic tidal inundation. At present, the latter is mainly a nuisance, affecting drains, gutters, roadways and reserves. However, as mean sea level continues to rise, the extent, depth and frequency of inundation and flooding will increase. Effects will include higher and more frequent flood and inundation levels with eventual permanent inundation of low-lying areas, salt-water intrusion of coastal groundwater, reduction in the effectiveness of drainage and other infrastructure.

Lake Macquarie City Council has commenced planning for these hazards through the preparation of Local Adaptation Plans (LAPs) for these suburbs. In line with the NSW Coastal Management Manual and the Coastal Management Toolkit, the selection of management options should be supported by a cost-benefit analysis (CBA). A robust CBA should be based on the expected costs and benefits of a range of intervention strategies rather than on a single best-estimate or design scenario. This requires a probabilistic hazard assessment that amalgamates the likelihoods associated with various coastal threats. Such a methodology has been developed for the open coast erosion hazard as described by Kinsela et al., (2016).

This project aims to build on the science of hazard assessment by:

- Developing an approach to assess the probability of the combined flooding/tidal/surge inundation hazard for the suburbs of Pelican, Blacksmiths and Swansea allowing for future sea level rise.
- Evaluating the probability distribution of Average Annual Damages at present and future times up to 2100; enabling an estimate of the probability distribution of the Net Present Cost of the combined hazard for a base case scenario of no intervention.

Introduction

Over the past decade, the approach to assessing coastal hazards in New South Wales has evolved from relying on the specification of a designated extreme event towards a risk-based approach where a range of events of different severity and their associated consequences are considered in developing management solutions. Often, the ‘likelihood’ of those events has been specified qualitatively, and a close read of the justification reveals that the qualitative terms assigned are based on ‘expert judgement’ with only limited consideration of the actual quantified probability of the coastal hazard event occurring. While descriptive terms of likelihood may be more palatable for some stakeholders, terms such as “possible”, “probable”, “likely”, and even “almost certain” and “never” are actually subject to substantial individual interpretation (Maboussin and Maboussin, 2018).

This is important given the increasing move towards deliberative governance (Twyford and Twyford, 2012). How do we clearly communicate issues surrounding climate change risk exposure to local communities, to enable informed decisions about their own levels of risk tolerance and the local adaptation management strategies that might be required?

Cost-benefit analysis (CBA) provides a useful way of provoking visceral engagement, by reducing the two dimensions of risk (probability and consequences) to a single cost dimension with which most people can engage. Of course, it is not the only available option. Indeed, while CBA is useful for assessing management options for evident coastal hazard risks, it needn’t be used exclusively and shouldn’t replace sensible landuse planning to manage risks which are both foreseeable and avoidable. Sensible landuse planning is one way of promoting the principle of intergenerational equity, which current CBA methods can discount.

This paper begins with overall discussion of the way in which the broad risk and CBA analytical framework can be applied to derive net present values for both existing risk and the results of actions to manage those risks.

We then present, in more detail, our methodology and preliminary analytical results aimed at undertaking a probabilistic hazard assessment for Swansea Channel, noting that the project is ongoing. The paper considers the combined inundation hazard (both catchment and ocean), which is the focus of the project being completed for Lake Macquarie City Council.

Broad Analytical Context

Cost benefit analysis involves the derivation of the net present value (NPV) of an annual series of the value of “benefits” accruing from potential management options, and a corresponding net present value of “costs”. The ratio of the two is termed the Benefit/Cost ratio. In practice, the net present value calculation uses “discounting” which is a reversal of the compounding calculation used, for example, in a compound interest calculation. The adopted discount rate (c.f. interest rate) reduces the present value of future benefits and costs. Over long timeframes, the analysis is very sensitive to the discount rate adopted and tends to greatly reduce the weight of costs to be borne by future generations.

As a cornerstone of CBA, a “base case” scenario needs to be established and analysed. In our example, the base case reflects a situation where no adaptive management action is undertaken to address increasing inundation due to sea level rise. By calculating a net present value for the base case, a subsequent comparative analysis can be used to determine the annual series of costs and benefits that result from any given management strategy. Subsequently, the net present value of costs and benefits and the benefit cost ratio of that action can be calculated.

The work presented here focusses on calculating a major component of the annual series of costs, being the value of damages resulting from the hazards of tidal, storm surge and catchment inundation, within the context of a changing future climate. Substantial sources of uncertainty mean that this projected annual series has a probabilistic nature.

For illustration, the annual probability density function of damages (~ present day, top panel of Figure 1) indicates that infrastructure and property that are well sited to match current conditions incur damage for most years (~65%) between an illustrative $0 and $20,000. Comparatively, the situation in 30 years’ time if no adaptive strategy is implemented with property and infrastructure repaired/replaced at the same location after damage, is also shown (bottom panel of Figure 1). The regular nature of astronomical tides means that the damage profile shifts, damage becomes inevitable and between an illustrative $20,000 and $40,000 will occur for ~65% of years.

Considering the damage cost probability example just discussed (Figure 1) could arise from a numerical experiment, such as repeated simulations within a Monte-Carlo modelling framework, risk can be reduced to an expected ‘value’ of damages calculated as:

$$D_E = \int_{\infty}^{\infty} f(x).x \ dx$$

$D_E = \text{Expected value of damages for future year being considered (\$)}$
$x = \text{Damages}$
$f(x) = \text{Probability density function of damages}$

The annual series of D_E represents a time series of annualised annual damages, which can then be discounted to NPV as part of Cost Benefit analyses. Calculations of this nature are regularly completed a part of damages calculations associated with the development of floodplain risk management strategies in New South Wales.

A more fine-grained analysis, which would output a probability distribution of NPV could be completed via Monte-Carlo simulation, or by discounting the probability weighted of each damage band for future years, instead of the representative, expected value of damages.

To link damage values to the real-world inundation hazard, two additional relationships are required:

- The relationship between water levels and damages within a given locality. This is being considered as part of our project, but is not the focus of this paper, beyond noting that methods exist and are commonly applied to relate, for example, over floor inundation depths to damages in residential properties.

- The probability of water levels exceeding elevations at the given locality, both now and into the future, considering sea-level rise and climate change. This problem is the focus of the remains of this paper.

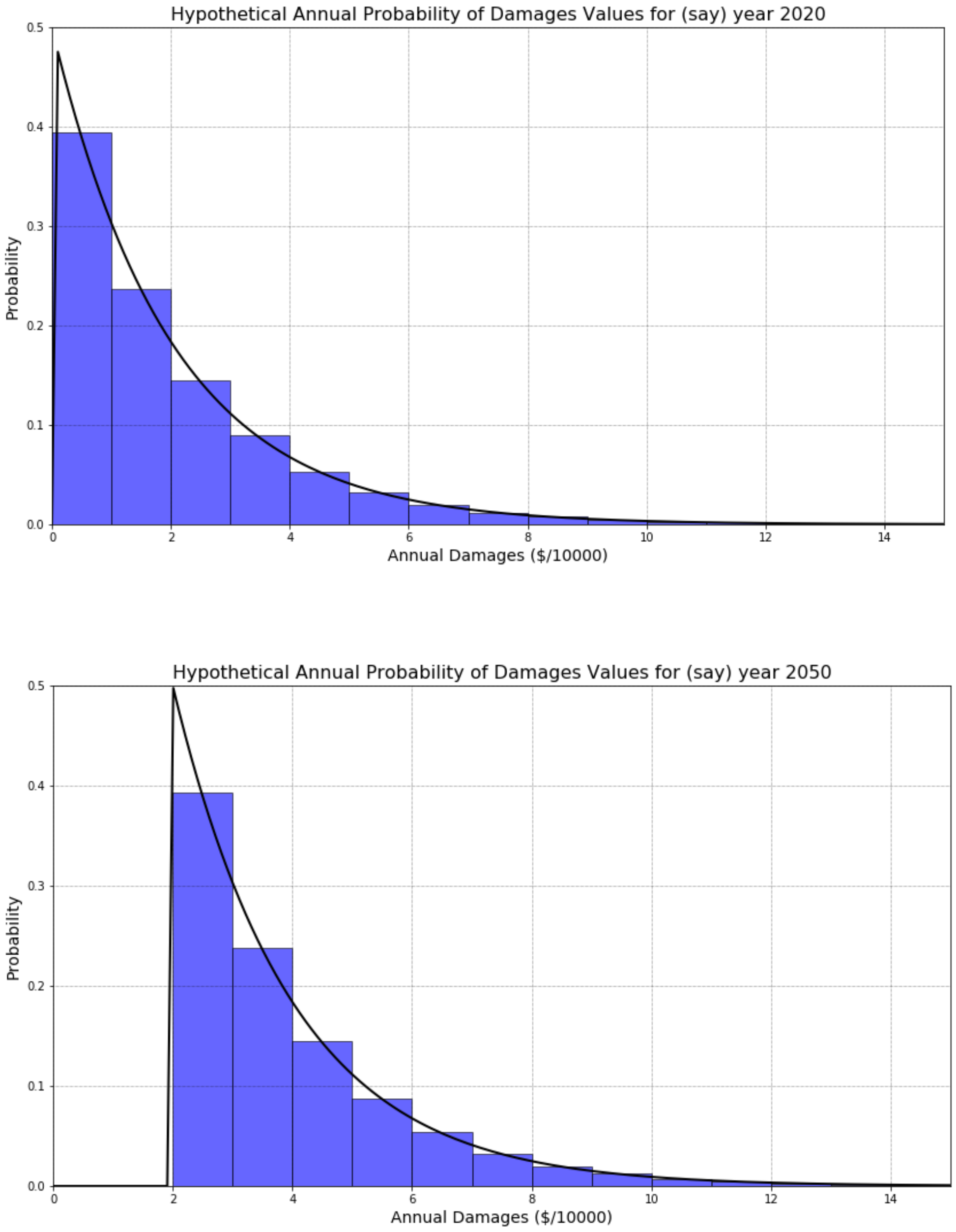

Figure 1: Hypothetical Probability Distribution of Damages for Present Day (top) and Future (with sea level rise - bottom)

Probabilistic Inundation Modelling

Our approach to the problem (Figure 2) is formulated to include Monte-Carlo modelling to develop a store of predictions from which the annualised probability distributions for water surface elevations (i.e. the inundation hazard), and subsequent annualised damages, can be derived.

The modelling engine comprises a simplified hydraulic model, described in the next section. The hydraulic model is run repetitively, over a predefined specified timeframe. For example, if adaptation planning decisions are required over a 100-year time frame, each simulation may cover the 2020 – 2120 period. For each repetition of the hydraulic model, a unique time series is derived for both the upstream (Lake) and downstream (Ocean) boundaries. The statistical models used to generate those time series is discussed in subsequent sections.

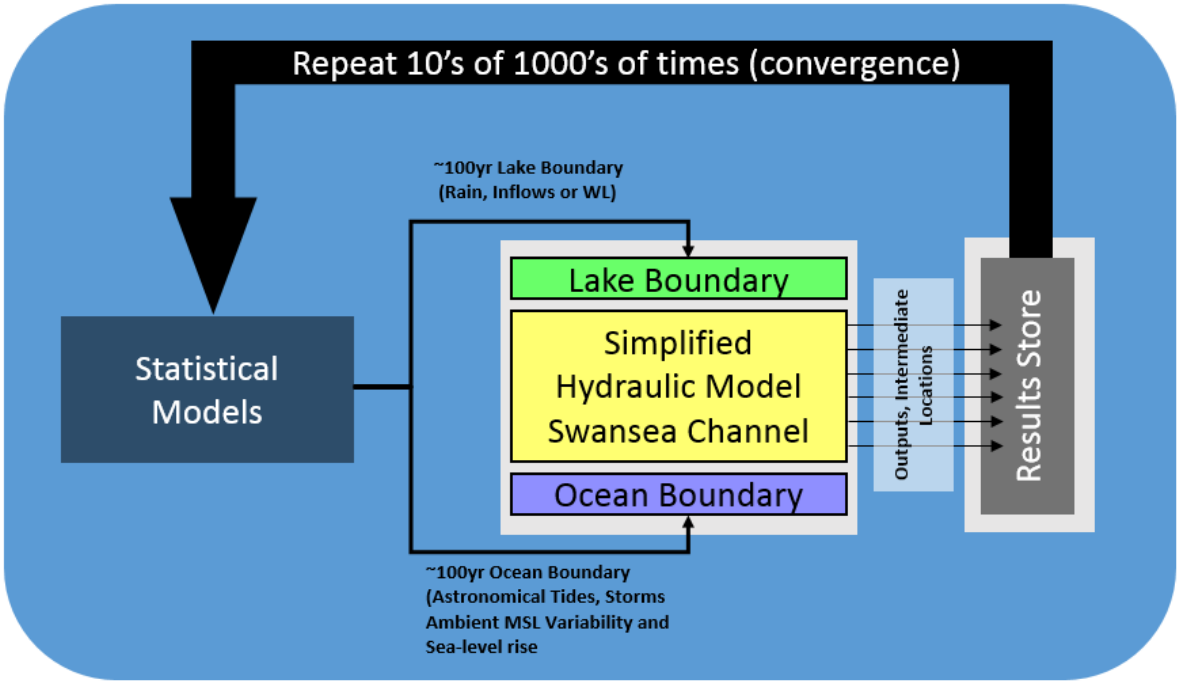

Figure 2: Modelling Framework for Determining Probabilistic Distribution of Water Levels

A set of results is derived for each simulation, comprising key water level exceedance events for each year of that simulation. The number of repetitions is set by that required to achieve stability of the probability distribution of key water level exceedance parameters. An example of this may be repeating simulations until a stable estimate of the 98% confidence interval for peak water level is achieved.

Hydraulic Model

A simplified hydrodynamic model has been developed for Swansea Channel (locality shown in Figure 3). The channel is around 6km long and experiences the steepest hydraulic tidal gradients of any Estuary in NSW. Along the channel, tides are attenuated by around 90%, with around 60% of that attenuation occurring upstream of Swansea Bridge (Manly Hydraulics Laboratory, 1996).

Alongside tides, the channel is also subject to substantial longitudinal variation in peak flood water levels. In the case of extreme flooding, the constraint at Swansea Bridge acts as a significant hydraulic control. Results from the most recent flood study of the Lake (WMA Water, 2011) demonstrate the behaviour of Swansea Channel during extreme floods.

The complex interactions of ocean tides, storm surge and catchment flooding require a model that can replicate these dynamic processes. However, as thousands of simulations of up to 100 years' duration are required, a fully featured hydraulic model would prove too computationally intensive to be practical.

The compromise adopted for the present study (Figure 4) includes channel and lake storages combined with channel friction, with the conservation of mass differential equation being solved using energy equation estimates of channel flow rates. Most hydraulic models solve Newton's second law of motion directly, that is solving two differential equations with friction included as a force. The approach we have taken provides a significant computational time saving.

Our model comprises a set of storage nodes separated by cross sections. At cross sections, Manning's equation is used to calculate discharge, based on cross section characteristics and the slope between adjacent storage nodes. At storage nodes, a mass balance relationship is solved based on the flow through adjacent cross sections. Water levels are then updated based on a stage-surface area relationship derived for the storage nodes. The cross-section characteristics and stage - surface area relationships were derived from a digital elevation model comprising data from an aerial depth sounding survey from 2008 and hydrosurvey completed between 2010 and 2012.

Preliminary results from ongoing calibration of the model at Belmont are illustrated in Figure 5. While broad Lake super elevation patterns are captured, the model is not yet replicating the range of tidal variations present during spring tide conditions. At present the Lake is incorporated as a single node, effectively meaning that the Lake is represented by a single basin which uniformly rises and falls with the tide. Preliminary investigations have indicated that the Lake actually contains two basins which can behave differently, depending on how quickly the water level is rising and falling, with Belmont located in the north basin. The north basin is directly connected to the upstream reaches of Swansea Channel.

Figure 3: Swansea Channel and Surrounding Suburbs

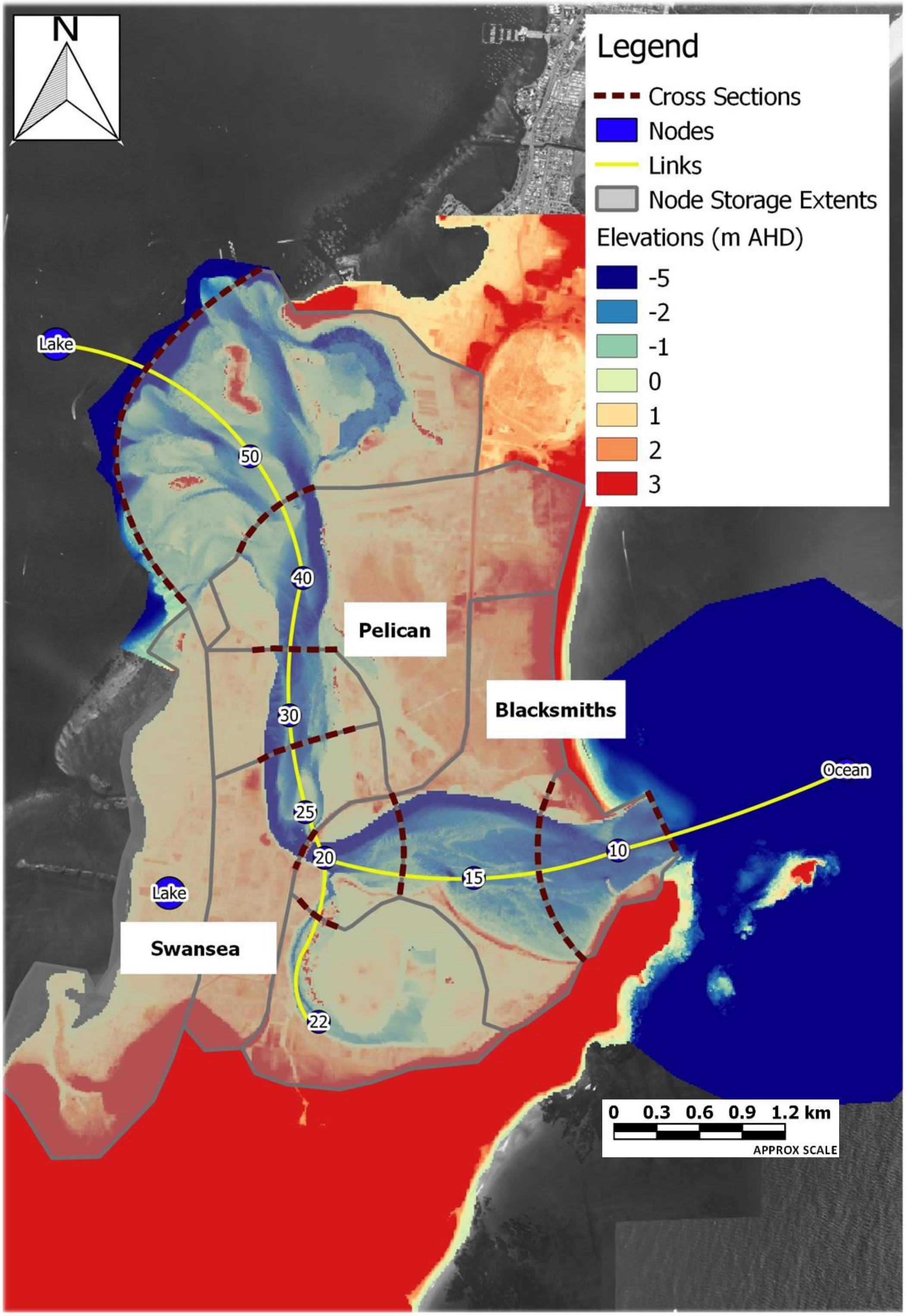

Figure 4: Configuration of Simplified Model

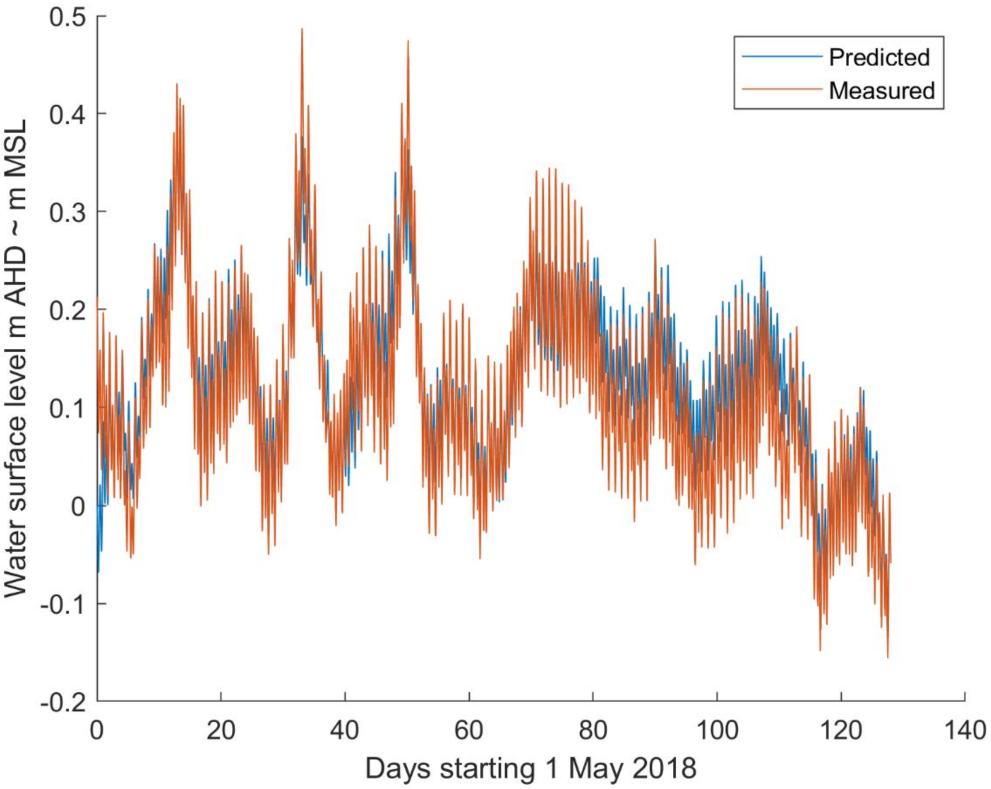

Figure 5: Preliminary Calibration Results - showing Model Predictions and Measured Water Levels at Belmont

Downstream Boundary (Ocean Flooding)

A statistical relationship for the downstream boundary has been largely derived from analysis of the Fort Denison tide record, which is the longest available in the Southern Hemisphere. This gauge is located some 90km to the south of the entrance to Lake Macquarie and thought to be broadly representative of ocean water levels in the central NSW region. The time series of annual average water levels was calculated for Fort Denison and then processed to remove the historical trend of sea level rise. The remaining time series contains the “noise” of annual mean sea levels that vary from year to year, typically no more than 6-8cm below or above zero. This noise can be somewhat correlated to large scale climatic patterns such as ENSO and the Interdecadal Pacific Oscillation (Callaghan et al., 2017; Holbrook et al., 2011; White et al., 2014).

The tidal record at Belmont (inside Lake Macquarie) was similarly analysed. Comparing results from the last 20 years demonstrated that:

- The trend of sea-level rise at Belmont has been almost identical to the trend at Fort Denison. Belmont’s mean level does sit a few centimetres above that calculated at Fort Denison, as the tide in Belmont is superelevated above the Ocean.

- Comparison of the patterns of noise remaining after detrending illustrated that year to year variation at the two sites is very similar, both qualitatively and quantitatively. Some variation is expected and present due to local effects such as catchment flooding.

Given the similarity in annual trend and variation between Fort Denison and Belmont, we are confident that conditions at Fort Denison are reasonably representative of the ocean at the entrance to Lake Macquarie. Accordingly, the longer record at Fort Denison has been analysed to derive a statistical model for ocean water levels in our model.

To provide a statistically sampled future sea level time series, four components need to be considered separately and added:

- Astronomical Tide.
- Tidal "Residual".
- 'Ambient' sea-level variability (as present in the historical time series of annual mean sea level).
- Future sea-level rise.

These are discussed in the following sections.

Astronomical Tide

Following detrending of the historical Fort Denison tidal record, it was processed using standard harmonic analysis[1] to extract the astronomical tidal constituents. Those constituents were then used to (i) construct a time series for the historic astronomical tide; and (ii) construct a future time series of astronomical tide. As astronomical tide is considered deterministic, the second time series will not vary between different simulations of our simplified hydraulic model.

Tidal Residual

A realistic time series is required of the daily to monthly scale variation from astronomical tide that occurs in response to weather systems, edge waves, ocean currents and other processes with that are predominantly random. The historic time series of tidal residual was determined from the Fort Denison record, by detrending and removing the astronomical tide. The result is illustrated in Figure 6 which illustrates the May-June period containing the historically significant coastal storm from 1974. While there are known issues with the available record over this period, the period serves as a useful illustration of its how the record has been decomposed.

---

[1] Using the methods of the UTide in Python https://pypi.org/project/UTide/

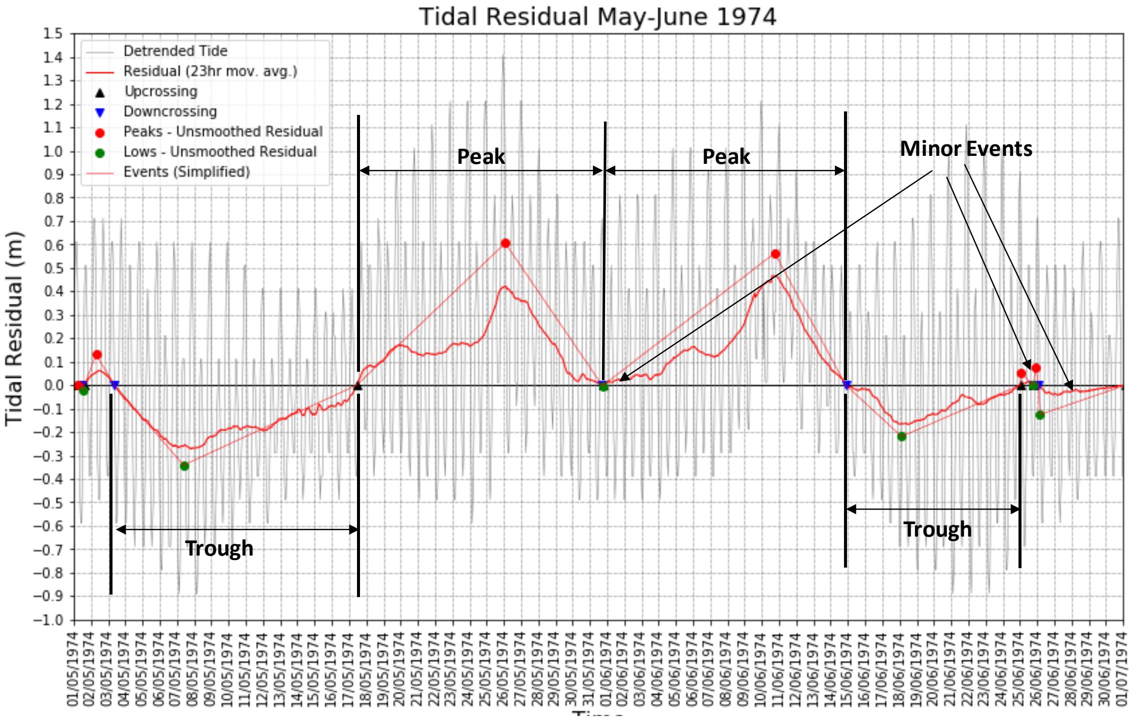

Figure 6: Decomposition of Historical Tidal Residual

The tidal residual was smoothed using a 23-hour moving average. This enabled clear discrimination of periods during which the residual was in a “trough” (below zero) or a “peak” (above zero). The actual maxima and minima of each of these peak and trough events (from the unsmoothed residual record), along with the time between up and down crossings of the smoothed residual signal were then extracted and stored in a database for subsequent analysis.

The two populations of recorded events (peaks and troughs) were then analysed separately. It was found that the residual is positive for around half the time, and negative for the other half, as was approximately expected. The duration of each event is plotted against the peaks and troughs in Figure 7. It was found that there is no obvious seasonal signal present along either dimension for both populations. It was also found that the maximum extent to which the residual diverges from zero is related to the length of the event. Put another way, for a given event length, the maximum divergence from zero must be at least more than a physically fixed limit. These limits are indicated on Figure 7.

Utilising standard peak over threshold methods for determining statistical extremes (Beirlant, 2004; Coles, 2001) a generalized pareto (GP) distribution was fitted to the tails of both the magnitude and length of both populations. The determined thresholds are as shown in Table 1. Below these thresholds, events can be sampled empirically when constructing a time series of residuals.

Table 1: Threshold Determination for Residual Event Extreme Modelling

Parameter	Peaks	Troughs
Magnitude	0.25	-0.2m
Length	400 hours	400 hours

The plots in Figure 7 do, however indicate that there may be some joint dependence between event length and magnitude, which is unsurprising given the apparent fixed physical limit described above. With reference to the top plot of Figure 7, for example, the largest storm surge events have historically been associated with events that last for shorter periods than 450 hours. Similarly, the longest duration historical events have never diverged much more than 0.4m from zero.

Following transformation of the data to a logarithmic scale, the nature of the relationships becomes clear. The transformation also enables the identification and removal of outliers. A combined method for fitting both marginal Generalised Pareto distributions for residual event length and peak Amplitude, at the same time as fitting the joint probability distribution was adopted, as illustrated in Beirlant et al. (2004). Sample quantiles from a fit to the combined tail of the trough data, using the commonly applied bivariate logistic model is presented in Figure 8. The tail of the model is fitted to data values exceeding 0.158 (Amplitude) and 165 hours (duration). This results in around 14% of the trough events being modelled in the tail (exceeding both thresholds). The resulting dependence (Alpha) parameter for the logistic fit of 0.52, indicates that the two parameters can be regarded as moderately dependent, i.e. neither fully dependent or fully independent (Coles, 2001).

Sea-level Variability

The more ambient, year to year variation in mean sea level has been analysed by examining the time series of noise generated by detrending the long-term time series of annual mean sea level at Fort Denison. The actual record at Fort Denison extends from 1915, but there were concerns that the first seven years contained three of the six largest positive annual variations from zero for the entire record. This was reflected in poor results from diagnostic tests which aimed to detrend the time series using a linear fit. Accordingly, the record was truncated by removing the first seven years, and a statistically robust linear fit was obtained. The resulting time series of noise is shown in Figure 9.

After considering a range of approaches that could be used to sample this aspect of future sea level for each hydrodynamic simulation, a first order autoregressive model (AR1) was selected. This model combines random sampling with some dependence of the previous year's variation of mean sea level from the long-term trend. The model reads as:

$$SL_Y = 0.360 \times SL_{Y-1} + \varepsilon(\mu, \sigma)$$

$SL_Y = V\text{ariation in annual mean sea level offshore of the NSW Coast, compared to underlying trend}$

$SL_{Y-1} = \text{ Corresponding variations in MSL from the preceding year}$

$\mu, \sigma^2 = \text{mean (0) and standard deviation (0.0231)of the random, normally distributed } '\varepsilon' \text{ term.}$

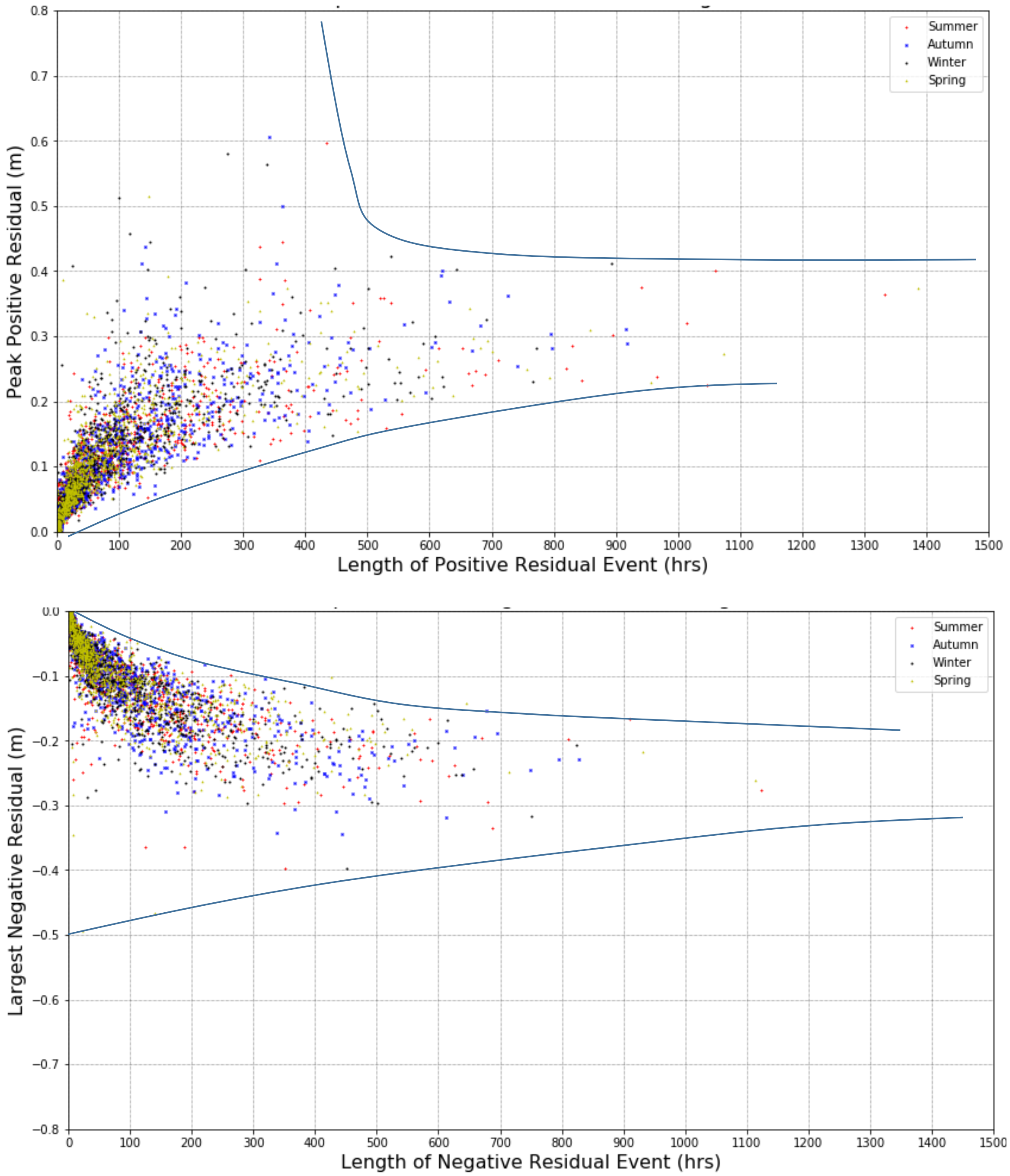

Figure 7: Maximum amplitude against Length of Positive (top) and Negative (bottom) residual events

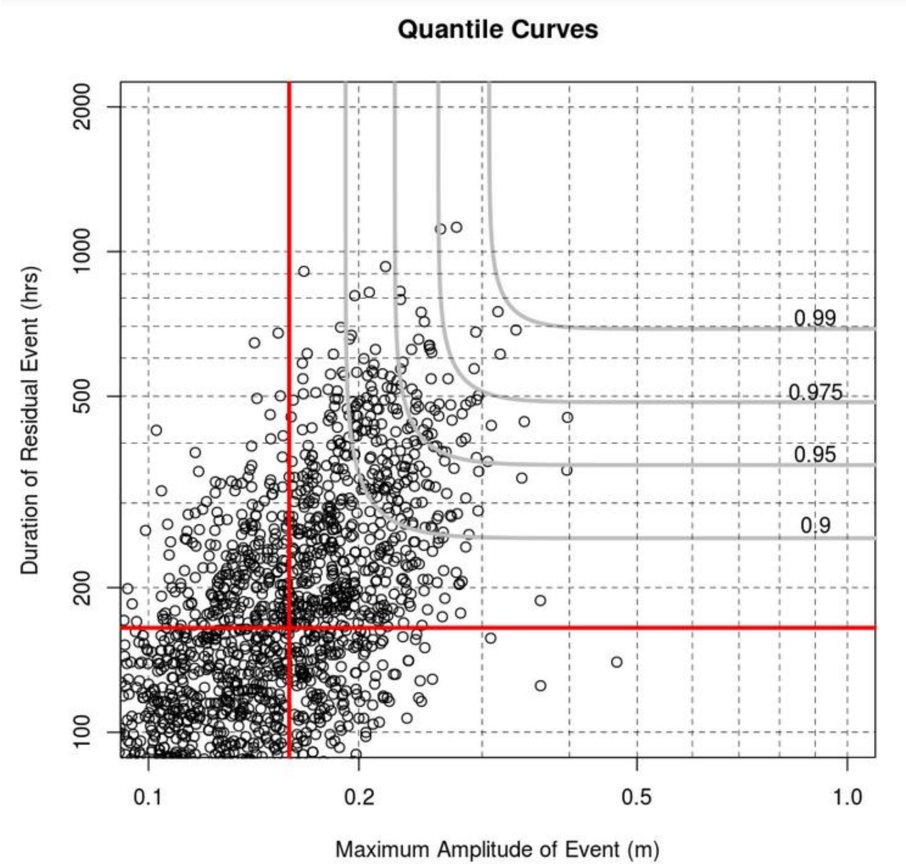

Figure 8: Quantile Plot for Fitted Bivariate Logistic Model to Maximum Amplitude and Duration of Negative Tidal Residual Events at Fort Denison

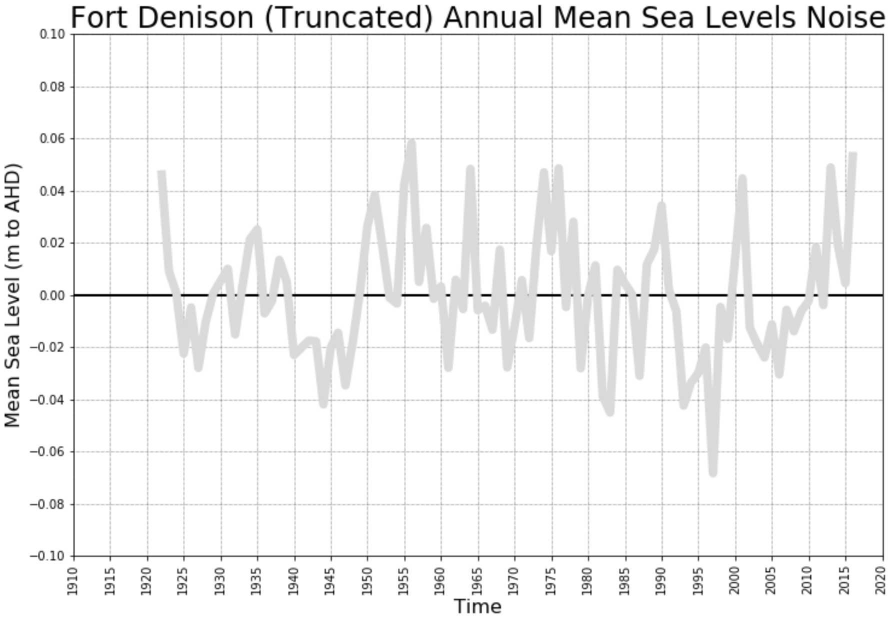

Figure 9: Variation of Annual Mean Sea Level from Long Term Signal

Five time series of randomly sampled sea-level variability have been generated with this model and are presented in Figure 10. These are provided here to demonstrate that the variability thus sampled has qualitative consistency with the measured record (Figure 9) and remains bounded, within a range that is comparable to that experienced historically.

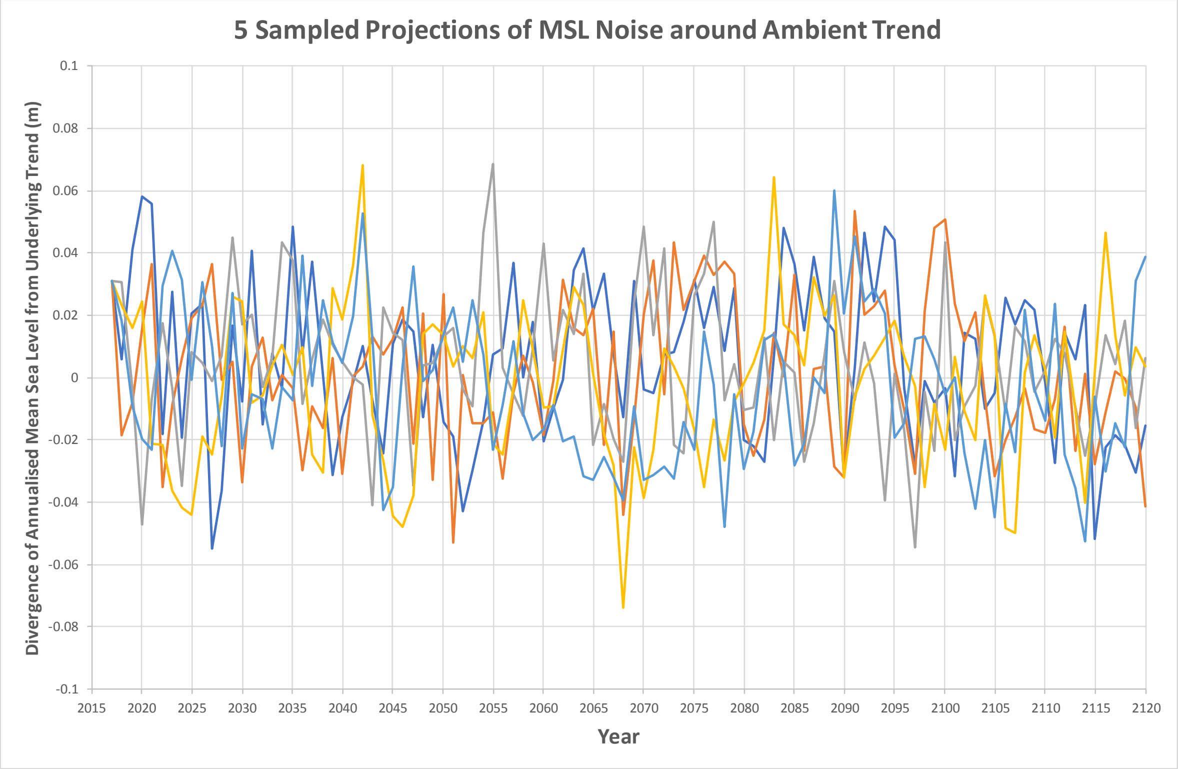

Figure 10: Sampled Time Series of Mean Sea Level "Noise" around Ambient Trend

Future sea-level rise

Several researchers have applied methods for stochastically sampling sea-level rise distributions based on model results from the IPCC (Hunter, 2010, 2012; Ranasinghe et al., 2015; Wainwright et al., 2014a; Wainwright et al., 2014b; Woodroffe et al., 2012). The IPCC's Assessment Report 5 (AR5) from 2013 provides guidance on how to use the range of sea level rise projections from climate models. The IPCC provided *likely* ranges of global sea level rise for four different projections or Representative Concentration Pathways (RCP's). *Likely* was defined as representative of the central 66% (or 17 to 83%) range of projections. These indicate that, by 2100, global mean sea level (GMSL) is projected to increase under a business as usual greenhouse gas scenario (Representative Concentration Pathway RCP 8.5) by between 0.52 and 0.98 m, or 0.26 to 0.55 m with significantly reduced emissions (RCP 2.6) relative to 1986–2005. (IPCC, 2013).

The equivalent local version of this range has been extracted from the global models used by the IPCC and are available for each council area in Australia via CoastAdapt [2] The *likely* range for RCP 8.5 at Lake Macquarie, is illustrated in Figure 11.

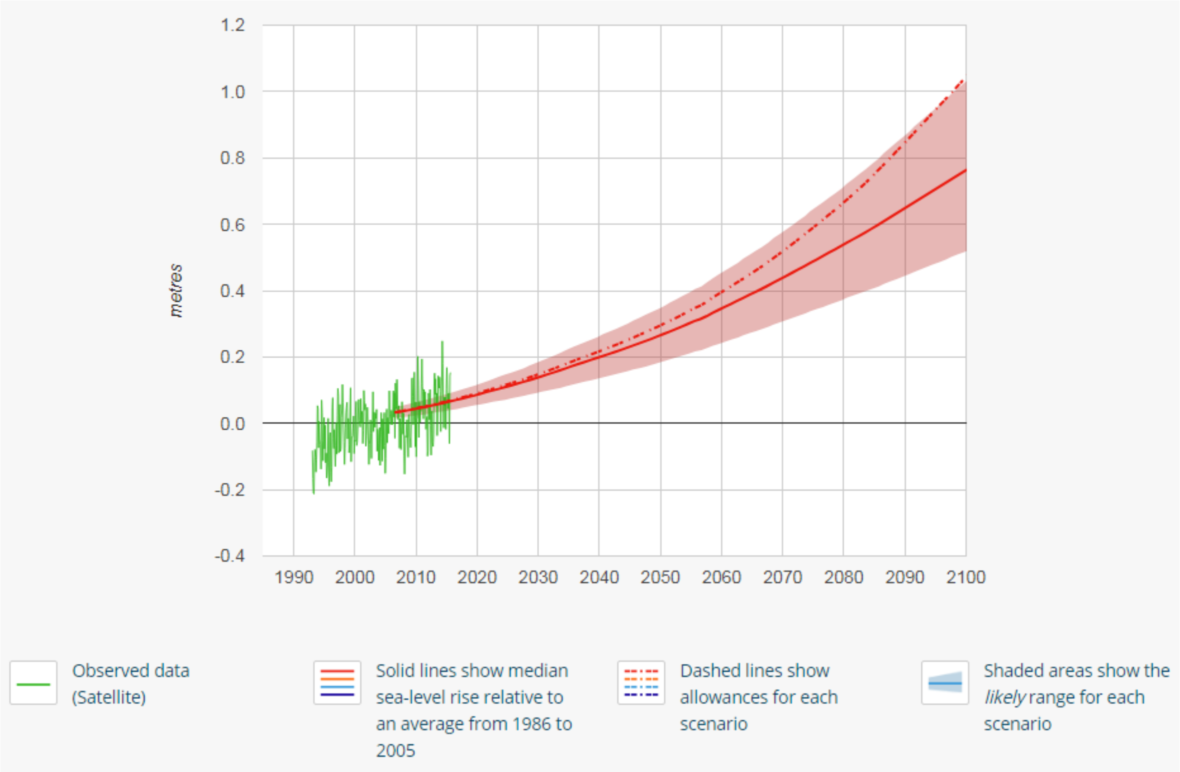

Figure 11: CoastAdapt Projections for Lake Macquarie, corresponding to RCP 8.5

Most researchers have indicated that the AR5 sea level range can be considered as being normally distributed for a given RCP. Although beyond the *likely* range there is increasing evidence pointing to an asymmetrical tail to the distribution. A recent review by the US National Oceanic and Atmospheric Administration (Sweet et al., 2017) along with the review by Horton et al. (2018) identifies evidence in support of a physically plausible upper limit of GMSL rise in the range of 2.0 to 2.7m by 2100, with recent work on Antarctic ice-sheet instability indicating that such outcomes may be more likely than previously thought.

Given the available guidance, randomly sampling a sea level rise projection is relatively simple. What is potentially more fraught with difficulty is selecting an appropriate RCP (or set of RCPs) and/or whether more recent information on sea level rise processes, such as an apparent acceleration in Antarctic ice melt should be considered before that research has been robustly examined by the IPCC. Discussions with stakeholders are ongoing regarding this issue, noting that LMCC's presently adopted sea level rise projection is closest to RCP8.5.

---

[2] https://coastadapt.com.au/sea-level-rise-information-all-australian-coastal-councils#NSW_LAKE_MACQUARIE

Upstream Boundary (Catchment Flooding)

Providing that the hydraulic model is reasonably calibrated, water levels in the Lake will respond in an appropriate way for most of the time. There are, however, two processes that require additional attention:

1. Catchment flooding, where runoff causes lake levels to rise, also affecting water levels in Swansea Channel (discussed this section).
2. Ongoing scour of the entrance channel in response to training of the entrance over 130 years ago. (discussed in the following section)

Catchment flooding requires slightly more attention. Firstly, it is noted that water levels in the Lake are subject to “fortnightly tides” whereby spring tides pump up the water level in the Lake. A typical response at Belmont over a 14-day spring -neap cycle is provided (Figure 12). This figure shows that the “mean” water level in the Lake can vary by amounts in the order of 0.15m.

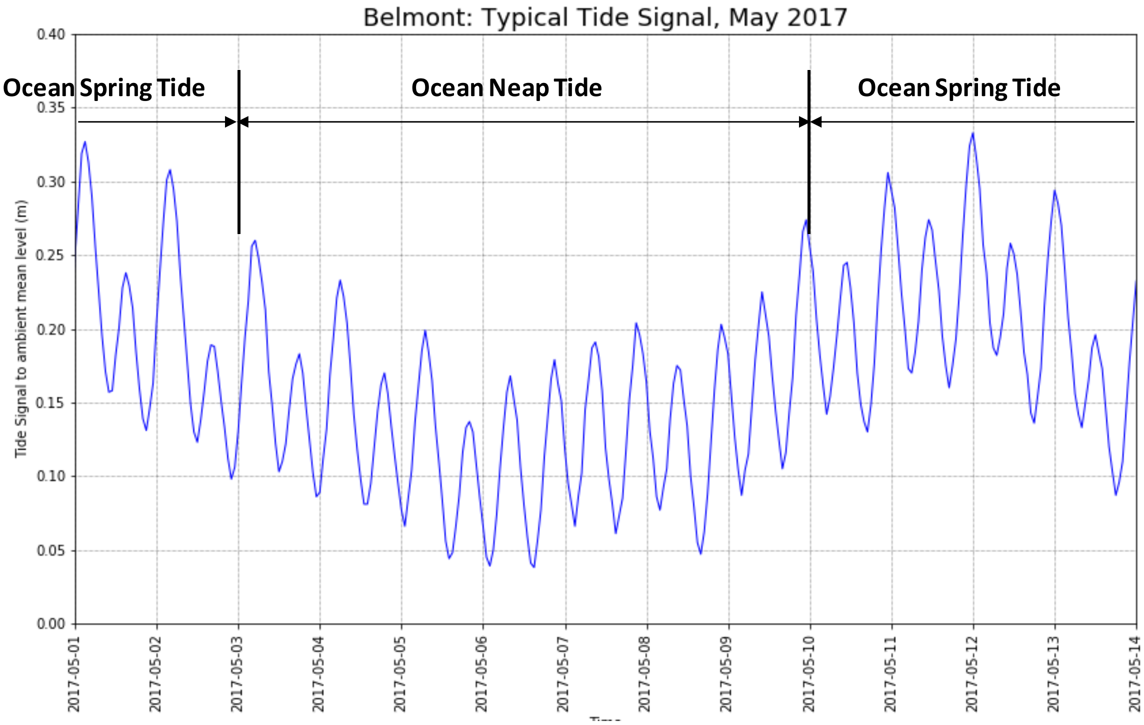

Figure 12: Effect of Tidal Pumping (i.e. fortnightly tides) on Water Levels inside Lake Macquarie

After considering the effect that the fortnightly tides have on tides inside the Lake, it was surmised that the tidal “residual” in the Lake water level record could be expected to be around 0.2m above that in the ocean under normal tidal processes. The Belmont tide record was detrended and analysed using UTide to derive the harmonic constituents, extract the astronomical tide and estimate the time series of tidal residual. For ocean surge events, the tidal residual inside the Lake tends to follow that in the ocean. However, rainfall causes further super elevation at Belmont. The time series of tidal residuals were compared and where the Belmont residual was greater than 0.2m above that of Fort Denison a catchment residual event candidate was extracted. These were then plotted and inspected, alongside the rainfall hyetograph recorded at Barnsley (North of Lake Macquarie), to remove any “false positive” events.

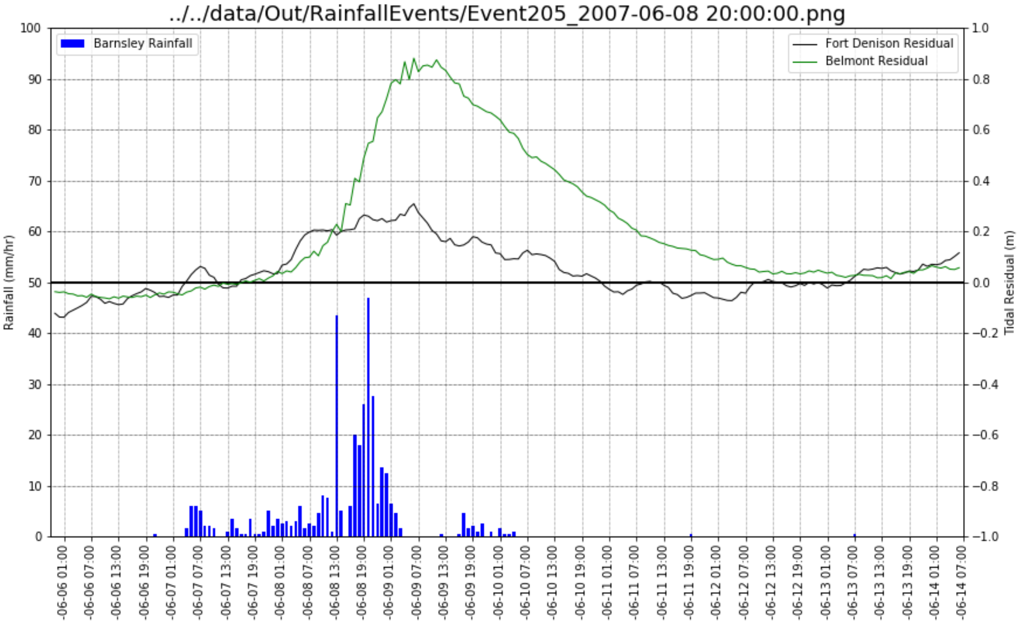

Figure 13: Demonstration of the “Excess Residual” Apparent inside Lake Macquarie following the “Pasha Bulker” storm of June 2007.

A database of excess residual and total rainfall for all rainfall events in the available record at Barnsley was then constructed. The “peak excess residual” for all events with more than 20mm of rainfall, resulting in an excess residual of more than 0.2m, is shown in Figure 14, plotted against rainfall. The relationship is strong but the lake response for a given rainfall could vary by up to around 0.2m around an expected value. Reasons for this include:

- Wetness of the catchment at the onset of rainfall.
- The period over which the rain falls.
- Changes in lake surface area as the water surface elevation changes.
- Spatial patterns of rainfall, only one pluviometer record was considered.

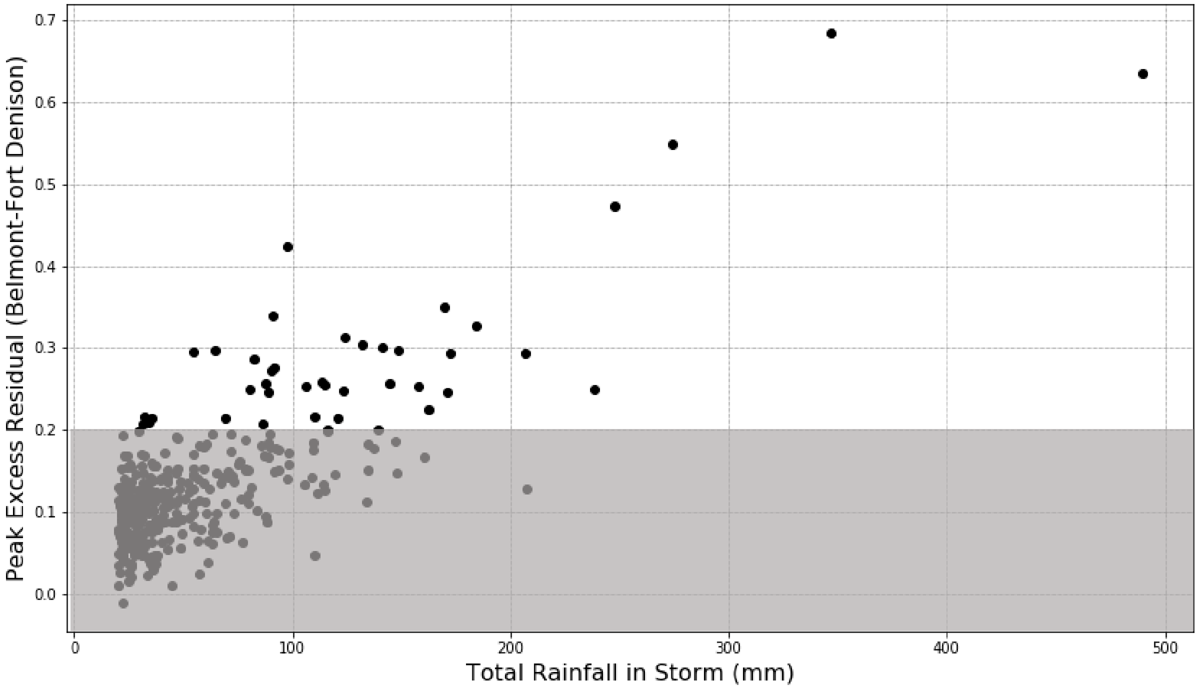

Figure 14: Excess Water Level Response in Lake Macquarie for Rainfall Events at Barnsley

Considering Figure 14, the impact of catchment rainfall on Lake water levels can be stochastically simulated by:

- Randomly sampling a rain storm volume. It is possible that local rainstorm volumes could be sampled using a relationship derived from the data presented in Figure 14 or, through intensity, frequency duration relationships published by the Bureau of Meteorology.
- Considering the variability of Figure 14, sample a residual excess value to represent the amount of water level rise in Lake Macquarie resulting from the rain storm. Analysis of the events that the peak excess residual in the Lake occurs within 12 hours of the peak rainfall during a storm.

The relationship will be compared and adjusted considering the findings of the most recent flood study (WMA Water, 2011).

Finally, there is some evidence that large rainfall events tend to correspond with large surge events. As an example, a low-pressure system can generate ocean storm surge, and then move onshore, causing rain to fall. To investigate this statistically, the timing of all peaks in tidal anomaly was compared with the timing of rainfall events. Where peaks in tidal anomaly occurred within a 96-hour window surrounding the rainfall event, those two events were linked.

Rainfall events are only slightly less likely to occur in conjunction with a negative residual (trough) than a positive residual (peak). Around a third of all residual events was linked to a rainfall event. There were also 551 identified rainfall events (out of 1257) where the rainfall peak was not linked to any residual event (i.e. peak rainfall was more than 48hours from a measured peak residual value). Plotting of the relationships of total rainfall volume (most closely related to lake water level rise) for linked events against the corresponding maximum deviation of the residual from zero showed no clear pattern.

The joint probability of positive tidal residuals against rainfall volume was analysed. The threshold selected using the methods outlined in Beirlant et al (2004)), resulted in the selection of all residual events which peaked at more than +0.11m, regardless of whether a rainfall event was associated with it or not. Again, a bivariate logistic model was fitted to the tail. This is shown in Figure 15.

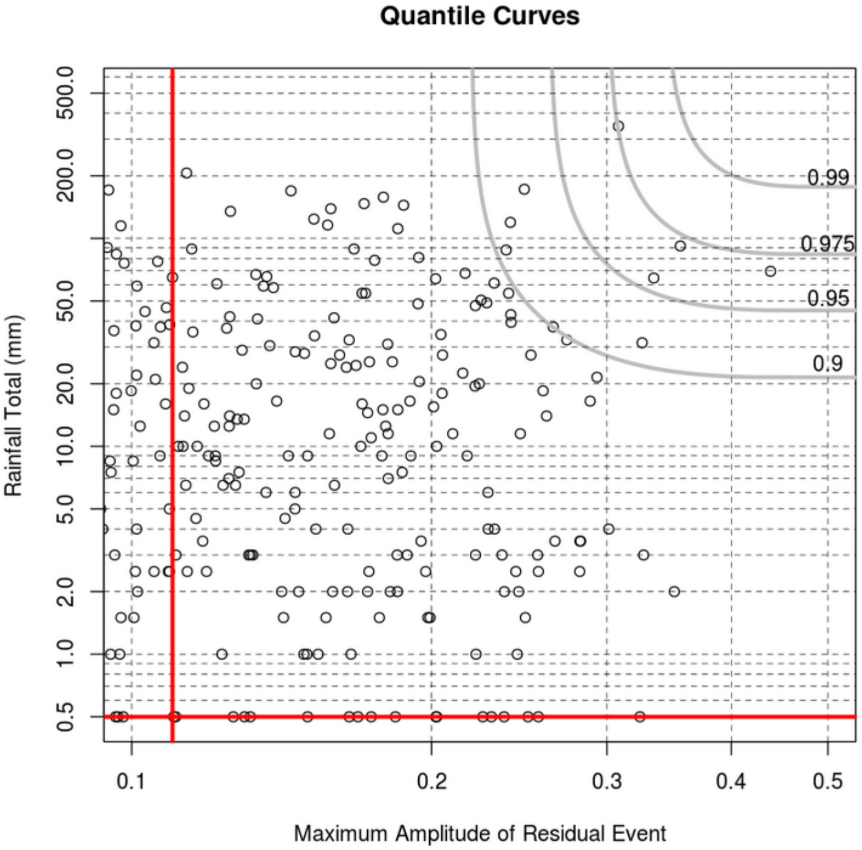

Figure 15 Quantile Plot for Fitted Bivariate Logistic Model to Maximum Amplitude of Tidal Residual Event at Fort Denison, and Total Rainfall Storm Volume at Barnsley

Overall, the fit shows that the two variables are practically independent, with a dependence parameter of 0.916 (where 1 indicates perfect independence and zero indicates perfect dependence). It is illustrative to note that the largest rainfall volume is not associated with either a positive or negative tidal anomaly peak.

It follows that sampling during Monte Carlo modelling should consider the timing of tidal anomaly and rainfall as being independent. During a given anomaly event (positive or negative), there is approximately1/3 chance that a rainfall event will occur. The peak of the rainstorm can be expected to occur randomly in time.

Ongoing Entrance Scour

Representing ongoing scour along Swansea Channel following training of the entrance in the late 1800's is relatively simple. Worley Parsons (2010) investigated the likely response of tides in the Lake to combinations of the evolving channel and sea level rise over time. To replicating the tidal response reported by Worley Parsons, the cross-sectional areas of the hydraulic model will be adjusted as simulations progress. Some allowance for uncertainty in the Worley Parsons estimates of tidal response could be made.

Conclusion

Analysis of measured data relating to water levels in the ocean and Lake Macquarie, and rainfall within the Lake Macquarie catchment has led to the derivation of relationships that will be used within a Monte-Carlo modelling framework to drive the boundaries of a simplified hydrodynamic model. Development of the model is ongoing, and the calibration efforts thus far show promise. Work is continuing to develop a robust integrated system that enables the simulations to proceed in a computationally efficient manner, providing information that will be used in subsequent damages assessments and cost benefit analyses. These will be ultimately used to inform adaptation planning for the suburbs surrounding Swansea Channel.

Acknowledgements

The work presented in this paper was funded and supported by the NSW Office of Environment and Heritage and Lake Macquarie City Council. The hydrometric data used in analysis presented here was supplied by Manly Hydraulics Laboratory, which collects and administers data on behalf of the NSW Office of Environment and Heritage. Elevation and Bathymetric data were provided by the NSW Office of Environment and Heritage.

References

Beirlant, J., 2004. Statistics of extremes: theory and applications. John Wiley & Sons Inc.
Callaghan, D.P., Couriel, E., Hanslow, D., Modra, B., Fitzhenry, M., Jacobs, R., 2017. Comparing extreme water levels using different techniques and impact of climate indices. Australas. Coasts Ports 2017 Work. Nat. 282.

Coles, S., 2001. An introduction to statistical modelling of extreme values, Springer series in statistics. Springer, London.

Holbrook, N.J., Goodwin, I.D., McGregor, S., Molina, E., Power, S.B., 2011. ENSO to multi-decadal time scale changes in East Australian Current transports and Fort Denison sea level: Oceanic Rossby waves as the connecting mechanism. Deep Sea Res. Part II Top. Stud. Oceanogr. 58, 547–558.

Horton, B.P., Kopp, R.E., Garner, A.J., Hay, C.C., Khan, N.S., Roy, K., Shaw, T.A., 2018. Mapping sea-level change in time, space, and probability. Annu. Rev. Environ. Resour.

Hunter, J., 2012. A simple technique for estimating an allowance for uncertain sea-level rise. Clim. Change 113, 239–252.

Hunter, J., 2010. Estimating sea-level extremes under conditions of uncertain sea-level rise. Clim. Change 99, 331–350. https://doi.org/10.1007/s10584-009-9671-6

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambrige, United Kingdom and New York, NY, USA.

Maboussin, A., Maboussin, M.J., 2018. If You Say Something Is “Likely,” How Likely to People Think It Is? Harv. Bus. Rev.

Manly Hydraulics Laboratory, 1996. Swansea Channel and Lake Macquarie Data Collection March-June 1996. (No. MHL770).

Ranasinghe, R., Wainwright, D., Callaghan, D.P., Duong, T., 2015. The relative contribution of sea level rise and storm erosion to net coastline recession, in: The Proceedings of the Coastal Sediments 2015. World Scientific.

Sweet, W.V., Kopp, R.E., Weaver, C.P., Obeysekera, J., Horton, R.M., Thieler, E.R., Zervas, C., 2017. Global and regional sea level rise scenarios for the United States.

Twyford, V., Twyford, V., 2012. The Power of’Co’: The Smart Leaders’ Guide to Collaborative Governance. Twyfords Consulting.

Wainwright, D, Lord, D., Watson, P., Lenehan, N., Ghetti, I., 2014. “Widely Accepted by Competent Scientific Opinion” Sea Level Projections for the Shoalhaven and Eurobodalla Coast. Presented at the 13rd NSW Coastal Conference, Ulladulla.

Wainwright, DJ, Ranasinghe, R., Callaghan, D., Woodroffe, C., Cowell, P., Rogers, K., 2014. An argument for probabilistic coastal hazard assessment: Retrospective examination of practice in New South Wales, Australia. Ocean Coast. Manag. 95, 147–155.

White, N.J., Haigh, I.D., Church, J.A., Koen, T., Watson, C.S., Pritchard, T., Watson, P.J., Burgette, R.J., Eliot, M., You, B., McInnes, K.L., Zhang, X., Tregoning, P., 2014. Australian Sea Levels - Trends, Regional Variability and Influencing Factors. Unpubl. Manuscr.

WMA Water, 2011. Lake Macquarie Waterway Flood Study.

Woodroffe, C.D., Cowell, P.J., Callaghan, D.P., Ranasinghe, R., Jongejan, R., Wainwright, D.J., Barry, S.J., Rogers, K., Dougherty, A.J., 2012. A model framework for assessing risk and adaptation to climate change on Australian coasts, Approaches to risk assessment on Australian coasts. National Climate Change Adaptation Research Facility.

Worley Parsons, 2010. Tidal Modelling of Lake Macquarie.