PLUVIAL FLOOD RISK AT AUCKLAND COASTAL SETTLEMENTS

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ABSTRACT

Many low lying coastal settlements and cities in New Zealand have ever increasing risk from rising sea level and precipitation due to climate change. Even if buildings and infrastructure are well above predicted sea inundation levels they are often still at risk of pluvial flooding due to ever rising tidal boundary conditions.

How should this risk be managed? What are the implications for stormwater infrastructure investment? What options are left when run-off meets high tide in low lying areas?

This paper explores the increasing demand on coastal outlets and low lying reticulation against a backdrop of high growth pressures in Auckland. It presents what we know about joint probability of rainfall and sea level to inform appropriate design standards for coastal infrastructure. For example what level of pluvial flood protection can be achieved and afforded in fully urbanised coastal areas?

Understanding of joint probability of rainfall and sea level is the key to informing affordable design parameters in such areas.

KEYWORDS

Joint Probability, Climate Change, Sea Level Rise

1 INTRODUCTION

This paper presents examples of flooding in some low lying Auckland urban areas where sea level limited the hydraulic grade of stormwater outlet infrastructure resulting in significant and frequent flood risk.

It presents the risk as defined by probability of occurrence and failure consequence to arrive at a best practicable option (BPO) at two sites.

In the process the paper asks how these areas can be managed over the long term in the face of increasing hydraulic challenge.

2 THE BASIC PROBLEM

Urbanised coastal land is inherently high value, but can be very low lying and prone to frequent flooding. Public expectations for flood protection in these areas are high. Ultimately, sea inundation could determine retreat as the only option for the next generations. But until then, what level of flood protection can be afforded through infrastructure improvements?

Auckland CBD has a large port, railway tunnel portal, arterial roads, and a stadium all on flat land at 3.5mRL. These assets rely on large stormwater culverts to manage flood risk as secondary flow paths are limited or unavailable. With rising sea level and increasing rainfall existing, culverts are expected to start failing more often. Already we have three recent closures of Tamaki Drive, an arterial road, and local roads such as Portland Road are regularly under water as rainfall and high tides coincide. Auckland is about to invest nearly $1 billion in new residential and commercial developments in Wynyard Quarter (all at 3 to 3.5mRL). It is increasingly important that the risk of culvert failure due to combined sea level and rainfall events are understood so that investment can be targeted appropriately in urbanised coastal areas such as Auckland.

Built assets (e.g. buildings, roads, railways, three-waters infrastructure), are all increasingly at risk from sea inundation. Currently 1,300 building structures are predicted to be inundated at present 1% AEP sea level. This figure is predicted to rise to 4,450 building structures with 1m sea level rise (SLR), and 9,900 structures with 2m SLR over the next 100 years.

Aside from the inundation risk associated with rare, extreme sea level events, more frequent high sea levels (e.g. mean high tide and mean high water springs) can significantly restrict outlet capacity of conveyance systems (reticulation and watercourses). This back-water effect is not usually a problem where buildings and infrastructure are over 4mRL. But in areas lower than 4mRL, hydraulic slope reduces markedly with small water level rises.

The following photos show the typical effects of King tides with storm surge at low lying coastal residential areas in Auckland.

Expensive Buckland’s Beach properties sit on land at 2.8mRL.

Fig 1   Bucklands Beach, November 2017 (source: Auckland Council)

Tamaki Drive, a coastal arterial road has been closed three times in the last year as road drainage becomes useless against high tides.

Fig 2   Tamaki Drive, January 2011 (source: NZ Herald)

Fig 3 SH1 Esmonde Road to Northcote, Auckland, Jan 2011 (source: Peter Mitchell, Auckland Motorway Alliance)

Stormwater engineers are being tasked with finding solutions to impossible problems at these low lying areas due to limited available hydraulic grade. But how likely are concurrent extreme rainfall and sea levels?   The joint probability of rainfall and sea level comes down to the level of dependence between storm surge and precipitation, both being due to weather conditions.

3 HOW SHOULD THESE RISKS BE DESCRIBED?

Multiplying extreme tide and rainfall AEPs suggests joint occurrence is highly unlikely. Table 1 below shows the joint probability of various combinations of extreme rainfall and sea level using ARIs. This way of describing risk is therefore not useful as it does not account for dependence of rainfall, storm surge and sea level.

Table 1 Joint ARIs for rainfall and sea level

Rainfall ARI	Tailwater ARI	NIWA water level mRL	Tailwater exceedance	Joint ARI
100	2	1.99	0.00005704	Minuscule
50	5	2.07	0.00002282	Minuscule
20	10	2.13	0.00001141	Minuscule
10	20	2.18	0.0000057	Minuscule
5	50	2.25	0.00000228	Minuscule
2	100	2.30	0.00000114	Minuscule

Since tide cycles are the biggest component of extreme sea levels, exceedance rather than Annual Exceedance Probability (AEP) would seem to be the best measure of sea level tidal risk to hydraulic performance. The risk of interest is what proportion of time can we expect the tide to be at or above a problem level.

The following examples used sea level exceedance curves (total time above problem hydraulic tailwater levels) to describe joint event ARIs (likelihood) and hydraulic failure (consequence). This informed options decision making based on more frequent/likely joint events which might occur within a generation.

4 INFRASTRUCTURE OPTIONS FOR STORMS AT HIGH TIDES

4.1 KEEPING STORMWATER OUT OF BRITOMART STATION TUNNEL PORTAL

Britomart Station is a vulnerable and highly critical asset with rail tracks sitting at approximately -5mRL. The land at the tunnel portal entrance is at 3 to 3.5mRL and close to the sea. Although manholes and catchpits are fitted with non-return devices, an HGL of 3 or more would risk water escaping the trunk system with an upstream catchment of 250ha and flowing overland into the tunnel portal.

Because of the close proximity to the sea, flooding is subject to influence by both rainfall and coastal storm conditions. Thus it is important to consider the joint probability of concurrent sea level and rainfall events in addition to the risk associated with each acting separately.

Minimum outlet size was determined by the need to keep the hydraulic grade line (HGL) below 3mRL with the various combinations of rainfall depth and sea level. In fact HGL is highly sensitive to sea level assumptions making it very important that both astronomical and meteorological influences and probability are well understood. Equally important is the probability of storm surge and rainfall acting concurrently.

Fig 4 below shows the location of the trunk stormwater reticulation and proposed supplementary outlet pipeline.

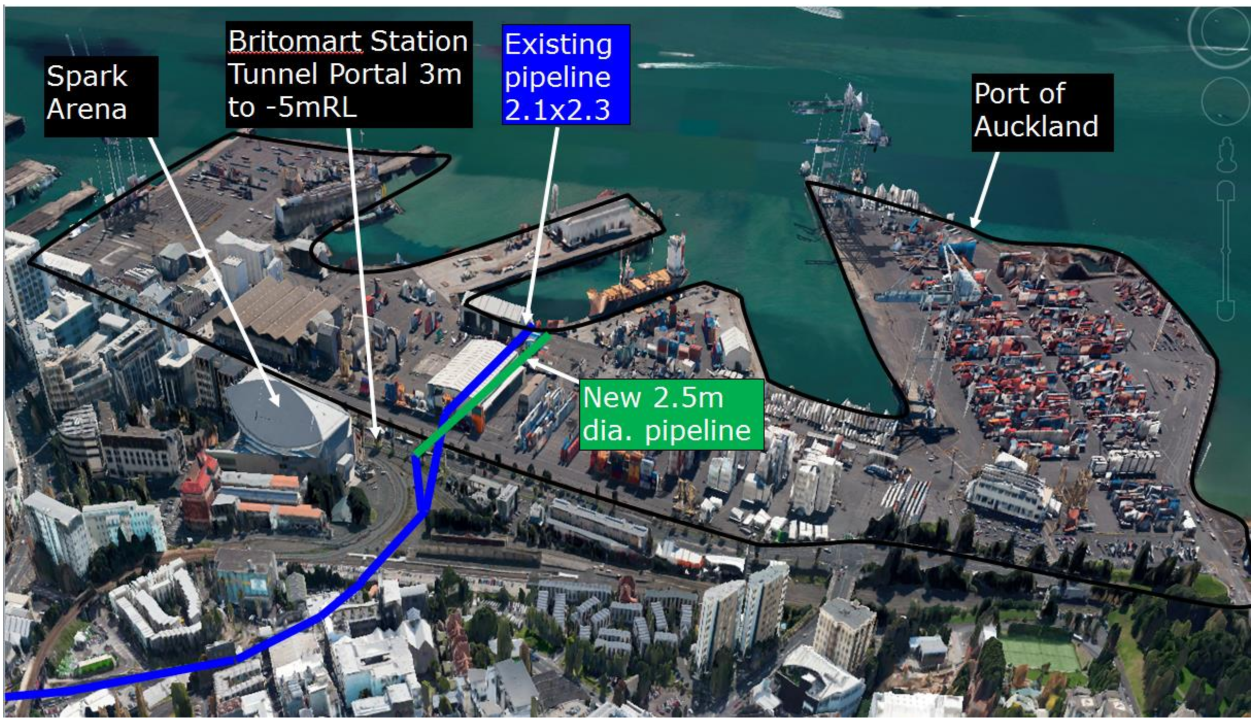


Fig 4 Plan for supplementary pipeline to the sea through POAL land

A hydraulic model was used to predict the water level at Britomart tunnel portal entrance (at the existing 2.1mx2.3m box culvert) for a range of sea level and rainfall combinations. The probability of these boundary combinations was estimated using sea level gauge exceedance data (refer to Annex 1) and adjusting for surge and SLR. $\alpha=1$ represents complete independence of storm surge and $\alpha=0$ complete dependence.

The models were run with two options[1] for a supplementary pipeline to the sea resulting in Table 2 below. Table 2 below shows the likelihood of various sea level-rainfall combinations which are predicted by the hydraulic model to fail the hydraulic criteria (i.e. cause HGL>3mRL). The supplementary pipe solutions were then sized to achieve HGL<3mRL.

[1] The two options are existing box culvert with a 1.8m dia. supplementary culvert, structural liner in existing box culvert with a 2.5m dia. supplementary culvert.

Table 2   Existing and upsized culvert performance

				Asset Protected?		Joint Probability (ARI)					
Outlet Size	**Rainfall (mm)**	**Sea Level**	**HGL at Britomart**	**Britomart Station**	**Old Railway Building**	**2017 α=1**	**2017 α=0**	**2059 α=1**	**2059 α=0**	**2100 α=1**	**2100 α=0**
2.1x2.3	105	1.89	3.04	No	No	1,000	167	57	24	27	12
	117	1.89	3.06	No	No	1,600	267	79	33	33	15
	140	1.6	3.04	No	No	1,000	167	89	51	36	25
	185	1.39	3.00	No	No	2,000	455	270	155	105	78
	216	1.89	>3	No	No	29,851	4,975	1,545	647	667	294
	216	1.2	3.05	No	No	1,244	498	461	292	250	192
	216	0.7	2.94	Yes	Yes	452	332	272	208	182	143
2.1x2.3 + 1.8 circ^2	117	1.89	2.87	Yes	Yes	1,600	267	79	33	33	15
	216	1.6	2.93	Yes	Yes	7,463	998	798	461	357	250
1.6x1.8 + 2.6 circ^2	117	1.89	2.91	Yes	Yes	1,600	205	79	33	33	15
	216	1.6	2.97	Yes	Yes	7,463	998	798	461	357	250

From the figures in the table it can be seen that the risk of hydraulic failure increases by an order of magnitude with increasing surge-rainfall dependence and sea level rise (i.e. ARIs get smaller from left to right across the table). For combinations of frequent rainfall (small storms) and extreme high tides the predicted increase to frequency is large.

The solution was sized to find the optimal balance between cost and flood risk, as described using hydraulic grade, rainfall ARI, sea level ARI, and joint rainfall-sea level event ARI. This is not the same as flood level ARI but thought to be a reasonable surrogate.

The performance of the two supplementary options reduces markedly with small sea level rises likely over the next 2-3 decades, but ensures the system can be maintained and has sufficient capacity for today's needs. The cost to provide future proofing against sea level rise out to 100 years was estimated to be an additional 60% and not affordable at this time. The solution can be retrofitted at a later date with pump systems if required depending on the amount of actual sea level rise which occurs over time.

4.2 KEEPING STORMWATER OUT OF PORTLAND ROAD

Portland Road is close to sea and low lying at 1.5m-1.6mRL. Tidal gates were added to protect against frequent sea inundation. However, when the gates are closed due to high tides, there is no protection against relatively frequent rainfall events. Although private property and buildings have been relatively unaffected, the road has been closed 2 or 3 times annually during the last ten years restricting access to property. Local political and media attention has prompted a Council investigation into options to address this increasingly frequent issue.

Fig 5   Tidal gates near Portland Road

Fig 6   Road flooding at Portland Road

The flood mechanism is that when the gates are shut, there is only enough storage for 10mm of rainfall under 3 hour duration. The gates shut at 1.2mRL which is exceeded 15% of total time.

Options included:-

- Raise the Road
- Diversion of the upstream catchment
- Major pump station

With present day sea level and rainfall volumes the road raising option can reduce the frequency from twice per year to once every 7 years. But with a 2050 sea level rise prediction of 0.5m, the gates would be shut 32% of time and frequency of flooding would be increased to once every 2.5 years.

The pumping option would provide a similar level of protection and could be increased to accommodate future sea level and rainfall rises. The additional cost to provide future proofing at this time is estimated to be an additional 100%.

The choice of option also had to weigh up the on-going operations and maintenance burden and risk of pump failure of the pump station option vs the more fail-safe option of raising the road.

4.3 DISCUSSION

Engineers are conservative by nature and necessity. They are tasked with designing infrastructure to never fail. But the odds at low lying coastal areas are in favour of nature in rare extreme rainfall and sea level events. However, significant improvement can be made to reduce risk for more frequent events less than "worst case" magnitude.

The decision process for investment in such flood mitigation schemes relies on a robust understanding of flood risk now, in future and hydraulic performance across a range of potential sea and rainfall combinations. The alternative options of do nothing or retreat may not be an acceptable choice in the near term.

The latest Ministry for the Environment (MfE) advice is to consult the community and use an adaptive process. The two examples above achieve the MfE suggested approach by allowing for future pumping to be retrofitted at a later date. Increasingly, pumped solutions or retreat may become the only available options.

For new infrastructure, the obvious choice is to avoid these areas and a conservative worst case approach is justified.

5 WHAT LEVEL SHOULD WE SET SEA LEVEL BOUNDARY IN MODELS?

The flow capacity of many low lying culverts in Auckland's CBD and residential areas is very sensitive to sea level assumptions. The hydraulic models confirm that sea level affects flow capacity more than rainfall estimates. This is because coastal outlet pipelines are typically flat graded and hydraulic slope reduces markedly with small water level rises.

Whilst large, long duration events such as those related to cyclones or ex tropical cyclones could typically include high tides, storm surge and high rainfall, most existing reticulation in coastal areas will be unable to provide the capacity required for protection of property and safety from flood hazards during these events.

The cost of achieving adequate capacity in these areas against a rising sea level is unaffordable and in some cases impossible to achieve, for most Territorial Local Authority Area's (TLA's). This leaves the TLA with no choice but to compromise the level of flood protection and future proofing offered to those areas at risk.

One suggestion is to set tide at the level exceeded 20% of time and test hydraulic performance against various sea level rise scenarios. The merits of this standard needs to be considered further against cost and affordability.

6 HOW DOES AUCKLAND COMPARE WITH OTHER AREAS?

Auckland has fewer assets in problem areas than the other three major urban areas of Wellington, Christchurch and Dunedin. In all areas, 100 year sea levels will become much more frequent with sea level rise making infrastructure solutions much less effective within a few decades.

Auckland is already spending significant funds to protect critical infrastructure such as Tamaki Drive, Northern Motorway and Auckland Airport against sea inundation. Sea level rise will also increase likelihood of culvert capacity failure at low lying areas in the near future. Gravity systems to address these low lying areas are becoming more expensive and less effective leaving pumping or retreat as the only options in the near future.

Table 3 Assets within 1.5m of spring high tide at four coastal urban areas

	Within 1.5m of spring high tide mark			
	Auckland	**Wellington**	**Christchurch**	**Dunedin**
Homes	1360	5008	9957	3604
Businesses	60	160	193	185
Roads (km)	56	58	201	72

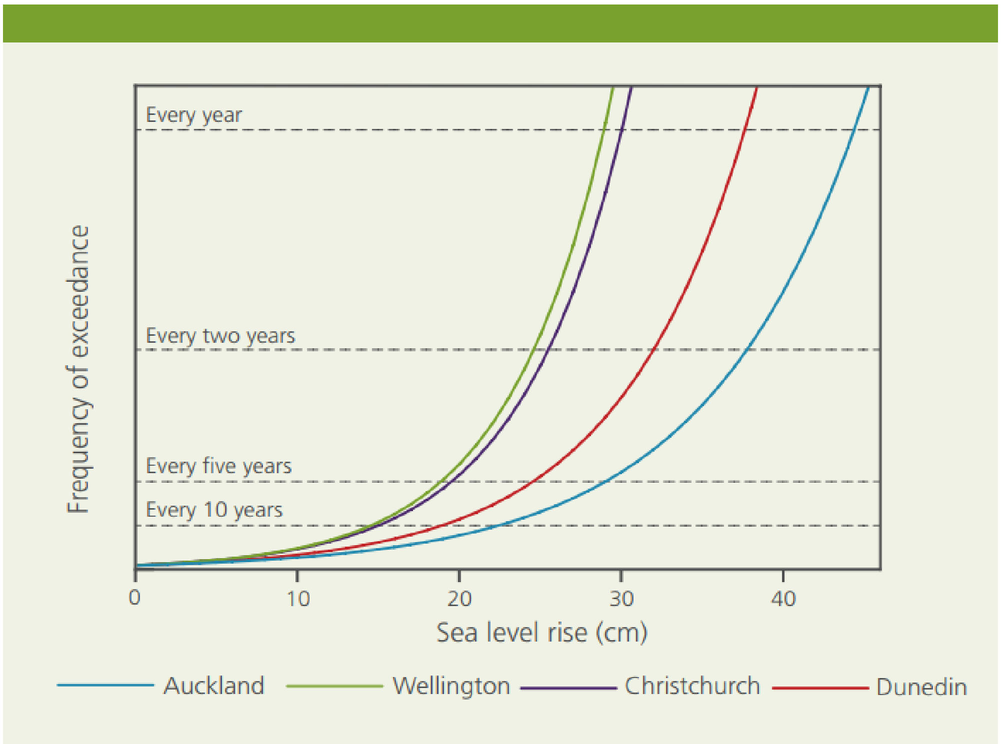


Fig 7 Increase in frequency of current 100 year ARI sea levels with sea level rise

7 SUMMARY AND CONCLUSIONS

1. Many culverts in low lying areas are at their capacity limits and are expected to fail more often as sea levels increase.

2. Typical codes of practise and design standards require infrastructure to be assessed against extreme sea level and extreme rainfall acting concurrently. The likelihood of joint occurrence of extreme rainfall and sea level is minuscule and a rethink using sea level exceedance is required.

3. In areas close to the sea, extreme, or even just frequently high, sea levels have marked effect on flow capacity due to backwater. Careful consideration of more likely joint events is required to understand this risk and inform decision making on best bang for buck.

4. Yet this approach will only work short to medium term. In the long term, sea levels will reduce culvert and stream flow capacity to the extent that engineering solutions will not work.

5. Two examples are presented to show how joint probability was used to optimise solutions balancing risk and cost. Future proofing adds significant additional cost, so the projects were designed to be stage able.

6. Auckland has fewer assets in problem areas than the three other major urban areas, but many are highly critical.

7. In all areas, 100 year ARI sea levels will be much more frequent making infrastructure conveyance solutions much less effective.

8. But significant risk reductions for critical assets can still be achieved in the near term, for more frequent joint rainfall-sea level events.

Acknowledgements

The Portland Road example was provided by Nadia Nitsche and Maria Utting.

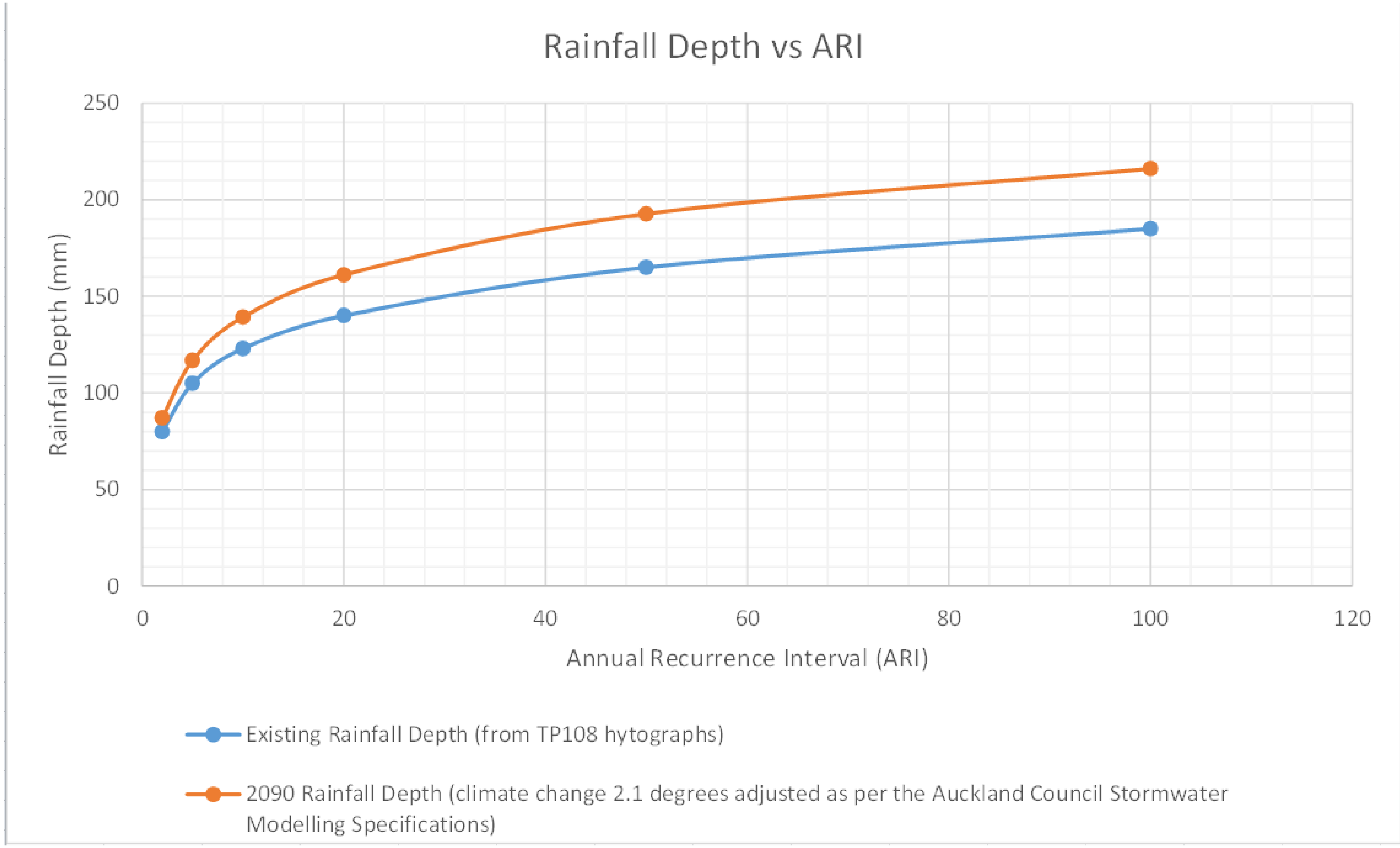
The POAL example was provided by Richard Smedley

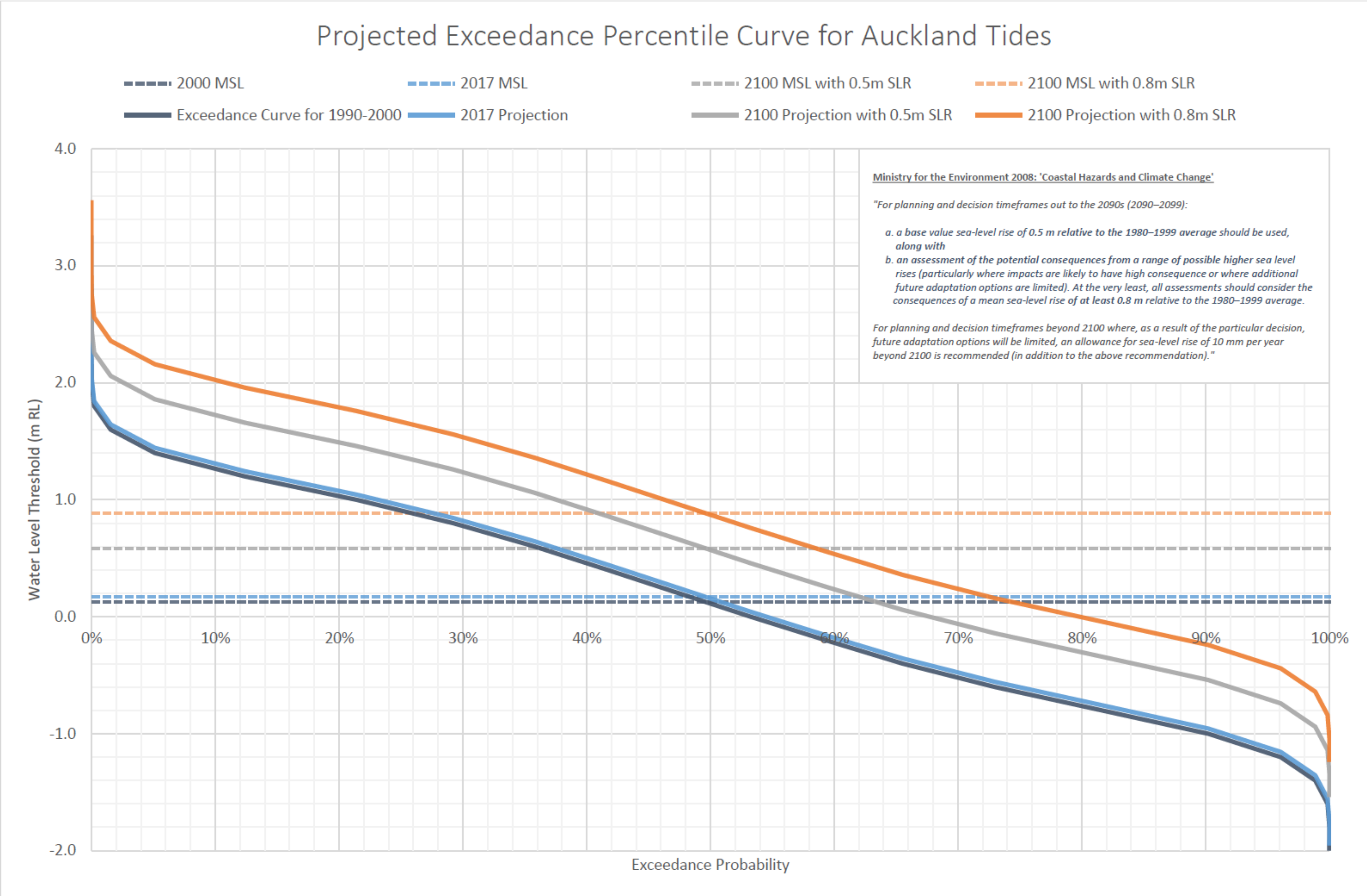
Exceedance probability curves were provided by Tonkin and Taylor Ltd

References

Preparing New Zealand for rising seas: Certainty and Uncertainty, November 2015, Parliamentary Commissioner for the Environment.

Annex 1 - Rainfall and Sea Level Probability




Projected Exceedance Percentile Curve for Auckland Tides
2000 MSL
2017 MSL
2100 MSL with 0.5m SLR
2100 MSL with 0.8m SLR
Exceedance Curve for 1990-2000
2017 Projection
2100 Projection with 0.5m SLR
2100 Projection with 0.8m SLR
Ministry for the Environment 2008: 'Coastal Hazards and Climate Change'
"For planning and decision timeframes out to the 2090s (2090–2099):
a. a base value sea-level rise of 0.5 m relative to the 1980–1999 average should be used, along with
b. an assessment of the potential consequences from a range of possible higher sea level rises (particularly where impacts are likely to have high consequence or where additional future adaptation options are limited). At the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 m relative to the 1980–1999 average.
For planning and decision timeframes beyond 2100 where, as a result of the particular decision, future adaptation options will be limited, an allowance for sea-level rise of 10 mm per year beyond 2100 is recommended (in addition to the above recommendation)."
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
Water Level Threshold (m RL)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Exceedance Probability