Update on sea-level rise projections for Wellington City

Supporting the 2020–2021 District Plan process

Prepared for Wellington City Council

March 2021

Prepared by:
R.G. Bell
M.J. Allis

For any information regarding this report please contact:

Michael Allis
Coastal Engineer
Coastal and Estuarine Physical Processes group
+64 7 856 1714
michael.allis@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 11115
Hamilton 3251

Phone +64 7 856 7026

NIWA CLIENT REPORT No: 2021051HN
Report date: March 2021
NIWA Project: WCC21201

Revision	Description	Date
Version 1.0	Internal draft version for co-editing	Feb 2021
Version 2.0	Added SLR tables in Section 3 and 4	1-Mar-2021
Version 3.0	Finalised draft for internal review	8-Mar-2021
Version 4.0	Final version	12-Mar-2021

Quality Assurance Statement		
	Reviewed by:	Dr Scott Stephens
	Formatting checked by:	Carole Evans
	Approved for release by:	Michael Bruce

© All rights reserved. This publication may not be reproduced or copied in any form without the permission of the copyright owner(s). Such permission is only to be given in accordance with the terms of the client's contract with NIWA. This copyright extends to all forms of copying and any storage of material in any kind of information retrieval system.

Whilst NIWA has used all reasonable endeavours to ensure that the information contained in this document is accurate, NIWA does not give any express or implied warranty as to the completeness of the information contained herein, or that it will be suitable for any purpose(s) other than those specifically contemplated during the Project or agreed by NIWA and the Client.

Contents

Tables

Figures

Executive summary

Wellington City Council (WCC) is embarking on a review and update of the District Plan.

In relation to low-lying coastal/harbour land and coastal-cliff frontages in Wellington, the revised District Plan needs to consider a planning timeframe of at least 100-years to give effect to the NZ Coastal Policy Statement (NZCPS). Under Policy 24 of the NZCPS, this includes "*taking into account national guidance*", such as the coastal hazards and climate change guidance (MfE, 2017), and "*the best available information on the likely effects of climate change on the region or district*".

WCC engaged NIWA to provide expertise on coastal hazards (excluding tsunami), including the effects of future sea-level rise (SLR) to inform and support the District Plan revision. This present report is the first output of this contract and provides:

- Present day mean sea-levels to use as the base sea level for future projections.
- An overview of local (relative) sea-level rise (RSLR) trends in Wellington from 121 years of average annual mean sea-level data at the Wellington Harbour tide gauge.
    - Over the entire record, the linear trend in RSLR up to the end of 2019 is 1.95 ±0.09 mm/yr.
    - Over the last six decades (1960–2019), the average RSLR trend is 2.82 ±0.19 mm/yr.
- Analysis of recent and future vertical land movement (VLM) caused by inter-seismic (between earthquake) subsidence which is prevalent across the Wellington Region.
- Synthesis of the latest national coastal guidance on SLR projections out to 100-years for New Zealand. WCC has requested to use only the RCP8.5 (median) and RCP8.5 H+ (83rd percentile) from the national coastal guidance.
- Forward projections, including mean sea level offsets, of RSLR, which includes recent vertical land movement trends over the 100-year planning timeframe.

The sea level analysis and projections are separated into two regions; the Harbour shorelines of Wellington City including the South Coast, and the western coast for Mākara and Ōhāriu. Projections are also provided in two vertical datums, given the drive to convert to the national 2016 vertical datum.

The RLSR projections at 2120 recommended for use in coastal flood mapping for the present District Plan revision are 1.43 m and 1.73 m above the 1985–2006 local baseline MSL (a baseline period also used by IPCC and the national coastal guidance MfE, 2017). These projected RSLR heights for Wellington Harbour also include an ongoing landmass subsidence trend of 3 mm/year, based on monitoring trends of inter-seismic ground motion over the past decade (but excludes any major seismic rupture event that could occur over the planning timeframe).

Adjusted to local RLSR projections for Wellington City and South Coast, the 2120 projections equate to 1.59 m (NZ RCP8.5 M) and 1.89 m (NZ RCP8.5 H+) in Wellington Vertical Datum 1953 (WVD-53)[1]. A further +3 cm offset is required to convert to local RSLR for the western coast

[1] To convert to the new recommended nation-wide NZ Vertical Datum 2016 (NZVD-2016), subtract 0.347 m from WVD-53 value.

(Mākara and Ōhāriu), which has a higher MSL due to the prevailing westerly winds and waves from Tasman Sea persistently piling water against the west coast.

This updated information is intended to be used to inform the coastal flooding and SLR mapping as inputs to the District Plan revision in accordance with the NZCPS Policy 24 requirements.

For stress-testing any coastal provisions of the revised District Plan, in terms of timing for the onset of specific adaptation thresholds, the lower RSLR scenarios from the national guidance should also be considered in the Plan revision to cover the cases of effective global emissions reduction occurring and therefore a slower onset of RSLR.

1 Introduction

Wellington City Council (WCC) is embarking on a review and update of the District Plan, which has been operative since 2000, with 83 completed plan changes. The District Plan, a mandatory planning document under the Resource Management Act 1991, sets out the objectives, policies and rules and associated map overlays that the WCC uses to manage development of the city's natural and built environment.

In relation to low-lying coastal/harbour land and coastal-cliff frontages in Wellington, the revised District Plan needs to consider a planning timeframe of at least 100-years to give effect to the NZ Coastal Policy Statement (NZCPS). Under Policy 24 of the NZCPS, this includes "*taking into account national guidance*" on coastal hazards and climate change (MfE, 2017), and "*the best available information on the likely effects of climate change on the region or district*".

The latest national guidance, MfE (2017), provides sea-level rise (SLR) projections generally for Aotearoa-NZ for the next ~150 years, while new information on vertical land movement rates in Wellington shows a trend of subsidence which will exacerbate SLR in Wellington.

1.1 Purpose of this report

WCC has engaged NIWA to provide expertise on coastal hazards, including the effects of future SLR to inform and support the revision of the District Plan. This present report is the first output of this contract.

This report builds on the previous reports and analyses, provides a synopsis of the most recent updates in SLR trends and forward projections, including locally relevant SLR, which includes recent vertical land movement trends. This updated information will be used to inform the coastal flooding and SLR mapping as inputs to the District Plan revision in accordance with the NZCPS Policy 24 requirements.

1.2 Background

The Wellington City district encompasses a wide variety of coastal environments, from the more sheltered Wellington Harbour, starting from the SH2 exit near Petone, through the CBD area and Miramar Peninsula, around the South Wellington coast (exposed to strong southerly storms), to the westerly-exposed coast and beaches of Mākara and Ōhāriu.

These different coastal exposures will manifest as spatial variability in wave setup, wave overtopping and storm-tide levels and hence in coastal hazard map overlays. However, this initial report focuses on the past trends and future projections of the base mean sea level (MSL) upon which all coastal-hazard processes ride on the back of, and which will shape future development and use of coastal/harbour areas.

Future SLR, or the rise in the base MSL, is caused by thermal expansion of the oceans, melting of glaciers and ice sheets and land water storage changes, and is strongly dependent on efforts to curb global emissions (IPCC 2019). SLR at the end of this century (2100) is projected to be faster than the recent century (1990–2000) under all global emissions scenarios. Beyond 2100, sea level will continue to rise for centuries due to continuing deep ocean heat uptake and mass loss of the global ice sheets and Antarctic ice sheets and will remain elevated for thousands of years (IPCC SROCC 2019).

SLR projections from IPCC and MfE (2017) refer to the rise in the ocean level only, however in the Wellington region, the landmass is generally subsiding, leaving aside major earthquake events (Bell et al. 2018). This vertical land movement (VLM) trend of subsidence, shown schematically in Figure 1-1, exacerbates the local sea-level rise for the City. The combination of SLR and VLM is strictly referred to as relative (local) sea-level rise (RSLR), as it aggregates both the rise in the ocean level and the subsidence of the landmass on which a tide gauge sits.

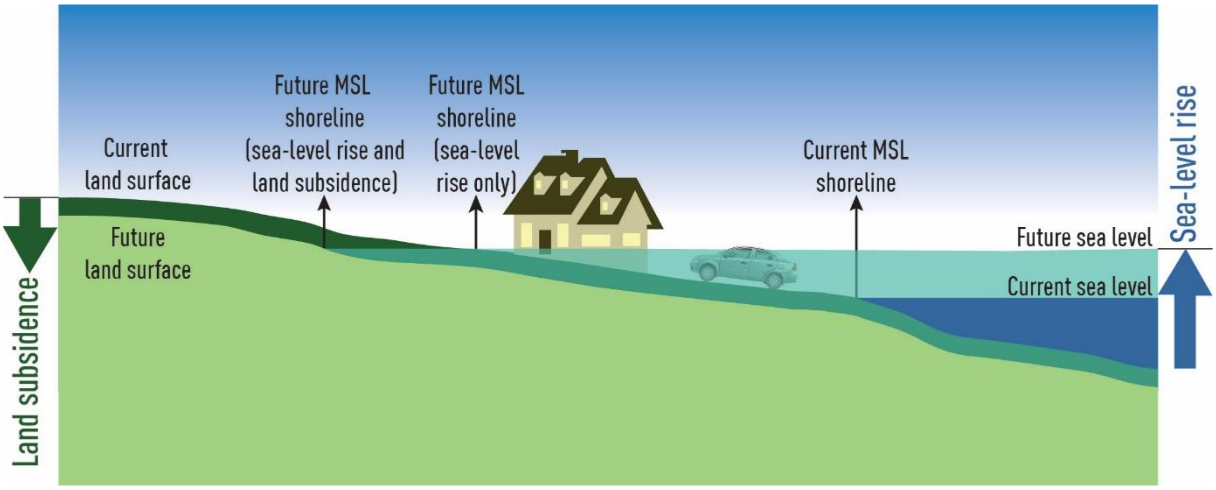


Figure 1-1: Schematic of how landmass subsidence exacerbates the rise in ocean levels that is experienced on land. *Source*: Graphic by A. Wadhwa (NIWA).

Land-based tide gauges, by default, measure RSLR directly as the vertical movement (uplift or subsidence) of the region's landmass is already factored into the measurements (compared with satellites that measure the absolute SLR of the ocean). The vertical movement of the land varies spatially across the region, and must be isolated from the recent RLSR trend, for separate inclusions into *future* RSLR projections along with the rise in ocean levels from MfE (2017) which do not include local vertical land movements.

It is RSLR that the City needs to adapt to, not the absolute rise in ocean levels. In Wellington, the ongoing subsidence exacerbates the local sea-level rise that the City will need to respond to in the future (leaving aside any major seismic rupture events that may or may not occur in the next 100-year planning horizon).

1.3 Previous SLR studies for Wellington

Previously, NIWA provided Greater Wellington Regional Council (GWRC) with a synopsis report on SLR trends and projections for the Wellington region in 2012 (Bell and Hannah 2012) and more recently, an update on SLR trends and vertical land movement (Bell et al. 2018).

In 2013, the inundation exposure for Wellington City was assessed for five SLR scenarios ranging from 0.6 to 3 m plus a storm event with a 1% chance of occurring each year (Tonkin + Taylor 2013). Further assessment of coastal vulnerability in the Wellington region to climate change and SLR was undertaken by Steele et al. (2019).

More recently, NIWA and Emeritus Professor John Hannah updated SLR trends up to the end of 2018 for long-term tide-gauge sites around New Zealand (including Wellington) as part of state of the environment reporting for the marine domain by the Ministry for the Environment (MfE) and StatsNZ (Bell and Hannah 2019). The datasets can be interactively viewed online[2].

Finally, forensic investigations were carried out in 2020 to estimate a previously unknown datum change in November 1944 when the Wellington Harbour gauge was upgraded and moved from Jervois Quay to Queens Wharf (Hannah and Bell 2020). While the possibility of a datum discontinuity during the 1944 upgrade was not considered to be a vital matter at the time, the issue has gathered importance over the last few decades due to its influence on determining long-term sea-level trend for Wellington.

[2] https://www.stats.govt.nz/indicators/coastal-sea-level-rise

2 Relative sea-level rise for Wellington

This Section describes the RSLR trend in Wellington and also unpacks the analysis on recent VLM, which is needed to add to future projections of RSLR for Wellington (see Section 3).

2.1 RSLR to 2018

Recent analysis on the Wellington Harbour tide gauge, operated by GWRC, was undertaken within a national project led by NIWA for the Ministry for the Environment and StatsNZ to support environmental reporting. The project updated the annual MSL series at six long-term sites for environmental reporting (Bell and Hannah 2019).

Further work in 2020 on the previously unknown November 1944 datum offset in the Wellington annual MSL series (Hannah and Bell 2020) resulted in a best estimate of the datum shift of 0.04 m. This offset was subsequently added to all the annual mean sea level (MSL) values for Wellington prior to and including 1944 for this present report, which slightly changes the long-term sea-level trend reported by Bell and Hannah (2019).

2.2 Annual MSL time series to 2019

Figure 2-1 shows the annual MSL series for Wellington Harbour up to and including 2019, noting the MSL for the 2019 year was more recently determined and the trend re-analysed by Emeritus-Professor John Hannah as part of the NZ SeaRise Project[3]. This recent analysis resulted in a slight change from the trend up to the end of 2018 by Bell and Hannah (2019) and available on the StatsNZ/MfE website.[4] Note: Wellington Harbour measurements of tide heights for 2020 have not yet been quality-checked and processed for any wharf subsidence, so were not included here.

Two different datums are presented in Figure 2-1 for the same annual MSL series for Wellington.

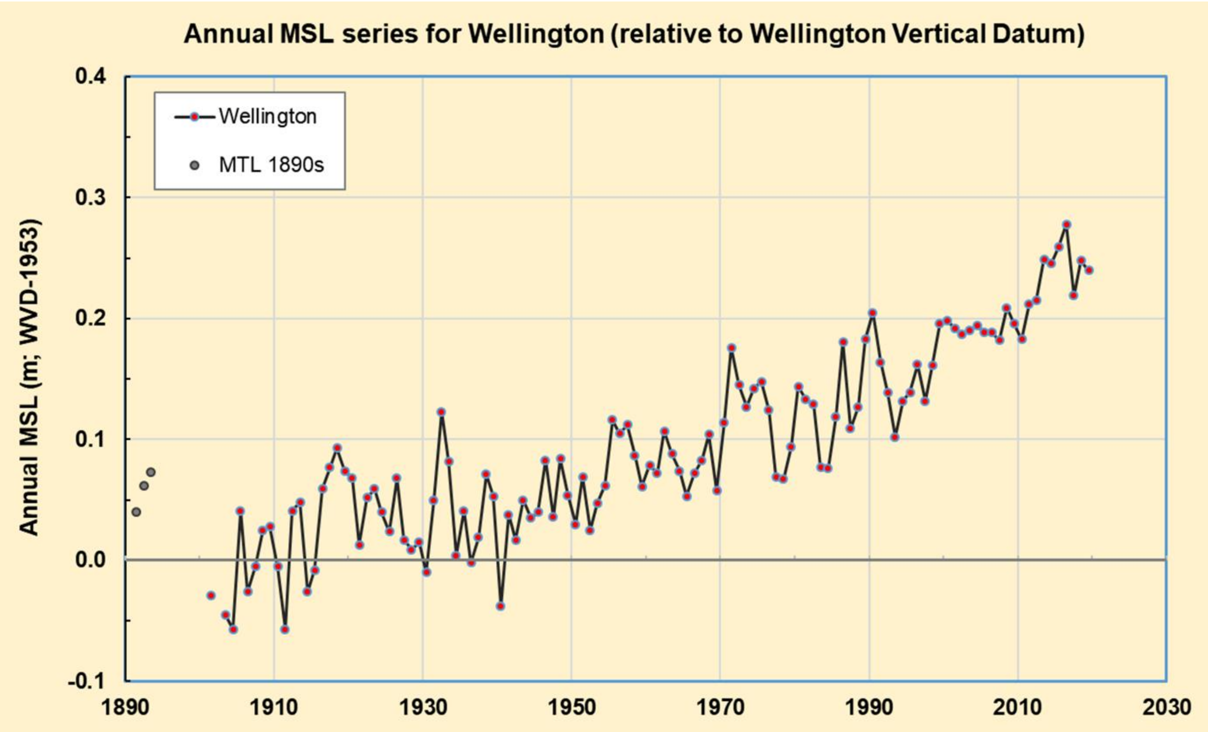
[3] https://www.searise.nz/
[4] https://www.stats.govt.nz/indicators/coastal-sea-level-rise

The top panel is relative to the historic Wellington Vertical Datum-1953 (WVD-53), which is the local vertical datum that up until present has been used for land-based elevations. The zero of the datum was established in 1953 by the then Department of Lands and Survey from tide gauge measurements covering 14 annual MSLs over the period 1909–1946 (Hannah and Bell 2012). To convert to the new recommended nation-wide NZ Vertical Datum 2016 (NZVD-2016), subtract 0.35 m from the historic series of annual MSL in terms of WVD-53, using the ABPB benchmark relationships before and after (Jan-2018) the Kaikoura earthquake[5].

The bottom panel shows the same annual MSL series relative to the 1986–2005 average MSL (heavy grey line on zero x-axis), which is the standard baseline used to anchor future projections of SLR, including by the Intergovernmental Panel on Climate Change (IPCC). For Wellington, the 1986–2005 average MSL was 0.164 m WVD-53. This value was added to future RSLR projections in Section 3.

Besides the upwards trend, the annual MSL series also exhibits substantial inter-annual variability, arising from the 2-4 year El Niño-Southern Oscillation cycle (with higher peaks during La Niña episodes) and the longer underlying 20–30 year Interdecadal Pacific Oscillation or IPO, which caused the jump in MSL in 1999–2000 (Figure 2-1) when the IPO switched to a negative phase.

[5] https://www.geodesy.linz.govt.nz/gdb/index.cgi?nextform=histhgt&sessionid=10160520279051615159386&mode=&code=ABPB



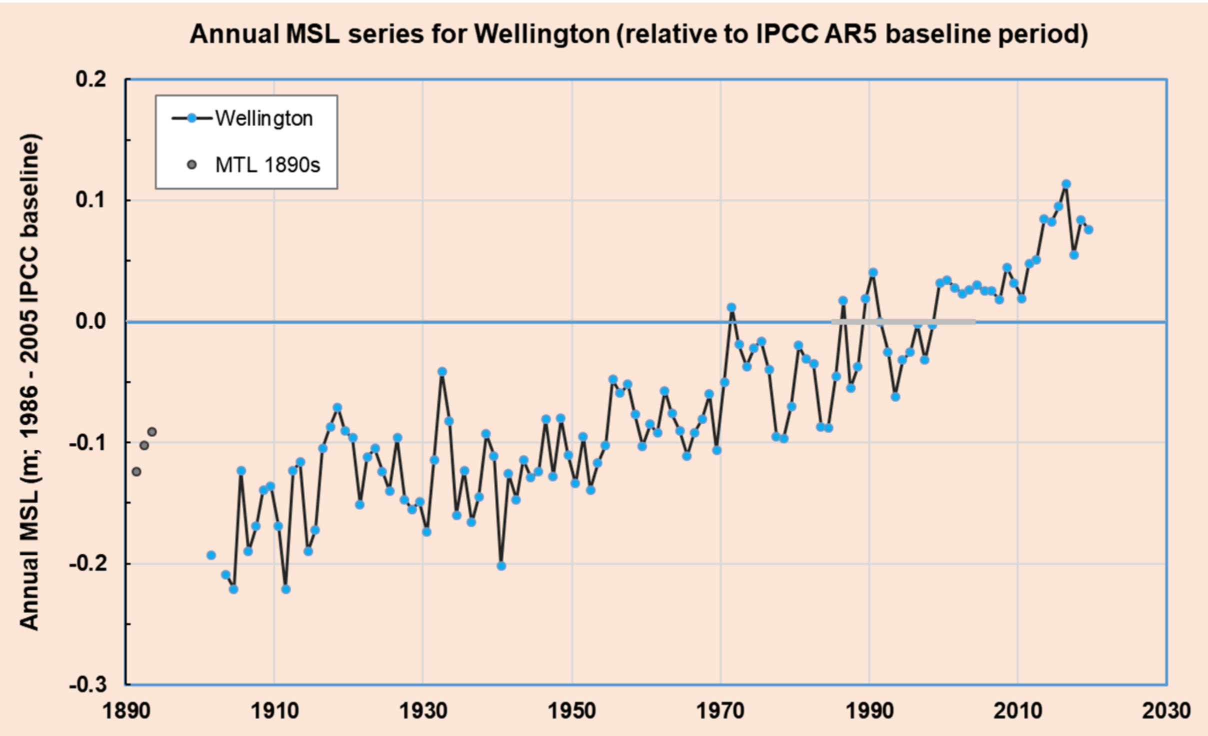


Figure 2-1: Annual MSL series from 1891 to 2019 for Wellington Harbour. *Source*: Original measurements: GWRC and LINZ; Processed annual MSL: Hannah and Bell (2020), J. Hannah (pers. com. for 2019 value). *Note*: values for 1891–1893 are sourced from archives listing only monthly averages of low and high tides (MTL), which are less reliable as a measure of MSL than more frequent data (Hannah 2004).

2.3 RSLR trend to 2019

Table 2-1 shows the updated trends in RSLR up to 2019 for Wellington for the annual MSL series presented in Figure 2-1.

The long-term record to 2019 comprises 121 years of average annual MSL, with gaps in the early part of the record (see Figure 2-1). The annual MSL, based on monthly mean tide levels (MTL's), for the early 1890s are not as accurate as MSL derived from regular sampling of the changing tide, so are weighted less in the trend analysis (e.g., Hannah 2004).

Further, the Wellington annual MSL series was also split approximately evenly into the early record up to 1960 and the subsequent era from 1961–2019 to compare trends over those ~60-year periods (Table 2-1).

Two reasons exist for this 1960 split:

- First, it consistently follows the analysis of global data sets of Church and White (2011) and Dangendorf et al. (2019), allowing a comparison with their results.
- Secondly, it allows the linear trend determined for the first part of the 20th century to be compared with the trend over the last six decades (which splits the records approximately in half (Table 2-1). Further, the split annual MSL data sets are at a length that should enable any recent change in trend or acceleration to be determined with some confidence, being mindful of the cautions raised in Douglas (2001) for extracting trends from records less than 60 years in length, because of the masking effects on annual MSL from variability of longer-term climate cycles (as discussed in Section 2.1).

Table 2-1: Long-term RSLR trends for the Wellington Harbour tide gauge up to the end of 2019. Units in mm/yr together with standard deviation in parentheses. *Source*: Bell and Hannah 2019; Hannah and Bell 2020; Hannah pers. com, for update to include 2019 as part of NZ SeaRise project.

Length of data set (Total no. of years available with a MSL)	RSLR for Wellington Harbour (linear trend)				
	1891–1960		1961–2019		Full data set to the end of 2019
	Years of data	Trend (mm/yr)	Years of data	Trend (mm/yr)	
1891–2019 (121)	62	1.0 (0.26)	59	2.82 (0.19)	1.95 (0.09)

Over the entire record, the linear trend in RSLR up to the end of 2019 is 1.95 ±0.09 mm/yr, which is somewhat higher than the global-average rate of ocean SLR of 1.56 ±0.32 mm/yr over a similar period from 1900 to 2018 (Frederikse et al. 2020).

For the last six decades, the average RSLR trend has more than doubled since 1960, from 1.0 ±0.26 mm/yr for the prior Wellington gauge records up to 1960, rising to 2.82 ±0.19 mm/yr for the more recent period 1960–2019 (Table 2-1). In comparison nationally, the rise in RSLR averaged across the 4 main ports (which includes Wellington) for the post-1960 era has doubled from 1.21 mm/yr since the pre-1960 era to 2.48 mm/year (Bell and Hannah 2019, and the MfE/StatsNZ web site.[6]

Essentially, there are two factors that explain these somewhat higher than historic trends:

1. The differential rise in ocean level in the SW Pacific compared with the global average SLR. Recently, Dangendorf et al. (2019) found a persistent acceleration in global SLR since the 1960s and demonstrate that this is largely associated with sea-level changes in the Indian-Pacific Oceans and South Atlantic. For the future, an analysis of global ocean-climate model projections for SLR in the seas around Aotearoa-NZ showed that SLR will be slightly higher (by up to 0.05 m by 2100) for the SW Pacific compared with the global average SLR (Ackerley et al. 2015).

2. The Wellington record has a definite signal from ongoing inter-seismic (between–earthquake) subsidence, which has only been monitored by continuous GPS stations over the past 10 years (see Section 3.2). If subsidence has been more prevalent in recent decades, then this would also have contributed to the higher RSLR trend for Wellington since 1960

2.4 Vertical land movement component of RSLR

Crustal faults within the Wellington region have all been all associated with varying vertical movements from past rupture events (Berryman & Hull 2003, Gibb 2012, McSaveney et al. 2006). These have produced sudden changes in relative sea-level rise, mainly uplift in Wellington City, but also subsidence in Hutt City (Begg et al. 2002) and will occur episodically in the future over geological timescales.

Such intermittent large rupture events on any regional fault cannot be relied on to occur, including whether they cause uplift or subsidence, over the coastal land-use planning horizon of the next 100 years. Instead, it is more prudent to factor in the ongoing secular (average) trend in VLM from crustal inter-seismic (between large events) processes including slow-slip episodes, into RSLR projections as recommended by national guidance (MfE 2017).

The NZ SeaRise project[7] is currently developing updated RSLR projections at local scales nationally, based on the aggregation of continuous GPS records and the spatially intensive satellite radar (InSAR) imagery and the latest global ocean-climate models, but the final projections are not yet available. In the interim, the latest average VLM rates for the Wellington region from GPS monitoring and InSAR satellite images between 2003 and 2011 (Levy et al. 2020) are shown in Figure 2-2.

[6] https://www.stats.govt.nz/indicators/coastal-sea-level-rise
[7] https://www.searise.nz/

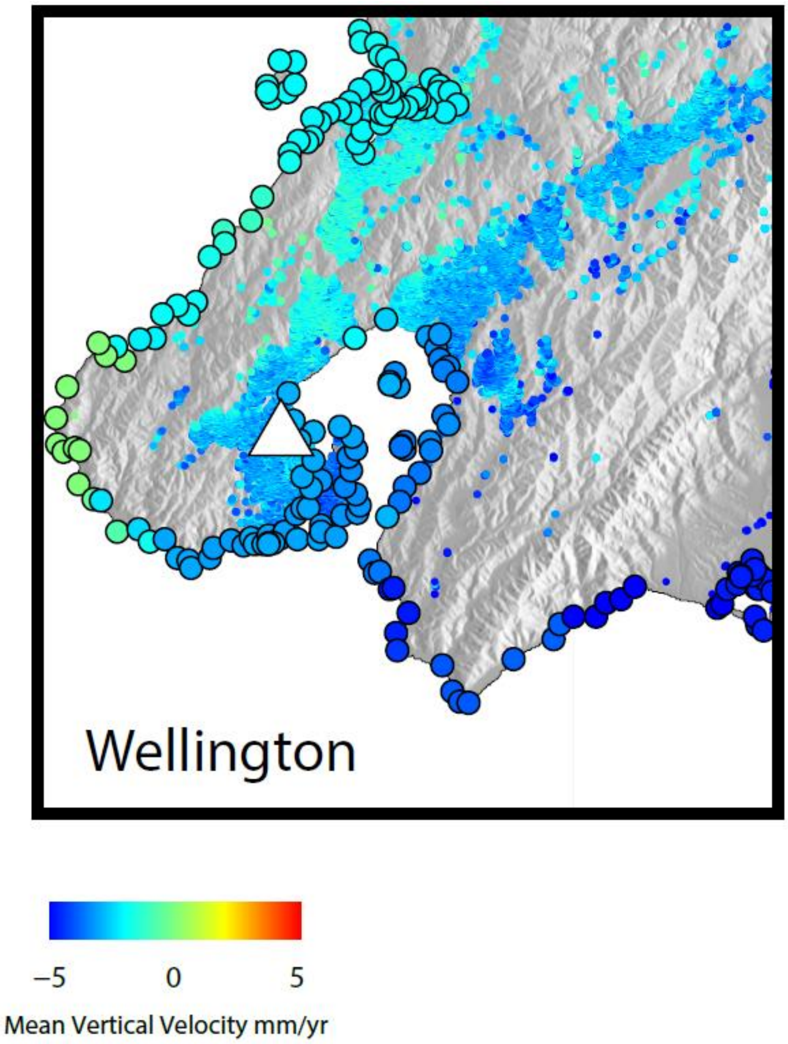


Figure 2-2: Averaged vertical land motion map for the Wellington region. *Notes*: -ve values (blues) = subsidence; +ve values (yellow/red) = uplift. Circles indicate location and mean VLM of coastal sites where updated RSLR projections will be produced by the NZ SeaRise project. The white triangle is the location of the Wellington tide gauge and nearby continuous GPS gauge. *Source*: Figure 7; Levy et al. (2020).

3 Projections of local RSLR for Wellington

This section outlines the components of local RSLR and aggregated future projections specific to Wellington City.

3.1 Present-day MSL

3.1.1 Wellington Harbour

The tide gauge in Wellington Harbour is situated on Queen's Wharf and is owned and operated by GWRC.

Normal practice for defining present-day MSL is to average the annual MSL values over 19-years to avoid aliasing the average MSL from long-period tidal variations that range up to the 18.6-year lunar nodal tide[8], and is also the averaging period for used by Land Information NZ (LINZ).[9]

Following the Kaikoura/North Canterbury Earthquake of the 14 Nov 2016, there was an immediate subsidence of the landmass in Wellington City, followed by a long post-seismic period of rebound that has more than countered the initial co-seismic subsidence of ~2 cm, as discussed by Bell et al. (2018). This time-varying response has complicated land levels relative to a relevant datum over the post-earthquake transition. For the "present-day" MSL, given most of the annual MSL values making up the average stretch back to 2001, pre-Kaikoura earthquake benchmark levels are used. These will need updating anyway in coming years, which can then incorporate the aggregated changes in VLM and hence benchmark levels since the 2016 earthquake.

Therefore, for the recent or "present-day" period from 2001–2019 (see Figure 2-1), for Wellington City and the Wellington South Coast the average **MSL** is either:

- **+0.215 m WVD-53** or
- **–0.135 m NZVD–2016** (using an offset of 0.35 m)

3.1.2 Western Coast – Wellington City

The single long-term gauge in Wellington Harbour is more influenced by oceanographic processes on the eastern side of Cook Strait and may not be representative of the MSL on the western coast of Wellington City, for example at Mākara and Ōhāriu.

An analysis was undertaken on the Mana Marina tide gauge inside Porirua Harbour entrance, which is also operated by GWRC, but over a much shorter period. The present-day MSL on the west coast is seen to be another 0.03 m higher than the Wellington Harbour gauge, explained by the prevailing winds and waves from the SW to NW across the Tasman Sea persistently piling water against the west coast.

As a result, a further 3 cm should be added to present-day MSL for these west coast settlements.

[8] Caused by the plane of the Moon's orbit around the Earth slowly varying by ±23° over 18.6 years
[9] https://www.linz.govt.nz/sea/tides/tide-predictions/standard-port-tidal-levels

Therefore, for the recent or "present-day" period from 2001–2019 (see Figure 2-1), for West Coast of the Wellington District (e.g., Mākara and Ōhāriu) the average **MSL** is either:

- **+0.245 m WVD-53** or
- **–0.105 m NZVD–2016**

3.1.3 Baseline MSL for future RSLR projections

When it comes to adding on future RSLR projections, an earlier 1986–2005 baseline for MSL is required, as the IPCC and international literature on projections for global SLR use this period as the zero for projections.

MSL for the RSLR projections baseline (1986–2005; mid-point 1996) for Wellington Harbour and South Coast areas is either:

- **+0.164 m WVD-53** or
- **–0.186 m NZVD-2016** (using an offset of 0.35 m)

These are used as the MSL baseline for projections in Section 3.3.

Applying the same 3 cm offset for MSL to the Western Coast areas of the City, MSL for the RSLR projections baseline (1986–2005; mid-point 1996) is either:

- **+0.194 m WVD-53** or
- **–0.156 m NZVD-2016**

These are used as the MSL baseline for projections in Section 3.3.

3.2 VLM projections

The average VLM for Harbour and south coast areas of Wellington City exhibit rates of around 3 mm/yr subsidence (refer Figure 2-2), which agrees with the average VLM subsidence of –2.7 mm/yr extracted from the 2000–2018 record of the continuous GPS gauge near the Wellington tide gauge by Bell et al. (2018). For the coastal mapping overlay, a single VLM rate of 3 mm/yr subsidence should be applied to future RSLR projections for Harbour and south coast parts of the City, given the uncertainty of either the current average rate continuing onwards at the same rate or the occurrence of moderate or larger earthquakes.

However, there is some discrepancy in VLM on the west coast when comparing shorter continuous GPS records[10] (e.g., Kāpiti, Paekakariki), which indicate higher VLM rates of 3.5–5 mm/yr (Bell et al. 2018; Table 4-1) with the lower mean VLM rates of 1–2 mm/yr subsidence from InSAR over a longer period from 2003 (Figure 2-2). Again, given the uncertainties in extrapolating the VLM rate forwards for RSR projections, the same −3 mm/yr rate should be applied to the costal hazard mapping overlays across all of Wellington City territory, where for the west coast, an approximate midway value between the two different types of datasets is adopted.

[10] https://www.geonet.org.nz/data/gnss/map; sites PAEK, KAPT

In any case, given the relatively short records for VLM and the uncertainty of trends in VLM rates in the coming decades for Wellington, the VLM component will need regular updating for future revisions of the District Plan.

3.3 RSLR projections to 2120

Figure 3-1 and Table 3-1 show the four SLR scenarios out to 2150 as recommended in the MfE (2017) coastal guidance for use in stress testing land-use plans and engineering/building projects when developing dynamic adaptive pathways planning (rather than second-guessing the future by choosing a particular scenario such as the best estimate or the worst case upfront). Also plotted is the annual MSL series from Wellington Harbour for comparison. This early comparison with tide-gauge data demonstrates that it may not be clear until mid-century, whether SLR will continue to follow higher scenarios or dip down to other scenarios, considering the climate variability in the tide-gauge data, the lag in ocean response to warming and global efforts at reducing greenhouse gas emissions. Therefore, it is important to keep options open, considering a range of possible futures and adapt as new monitoring information and projections come to hand.

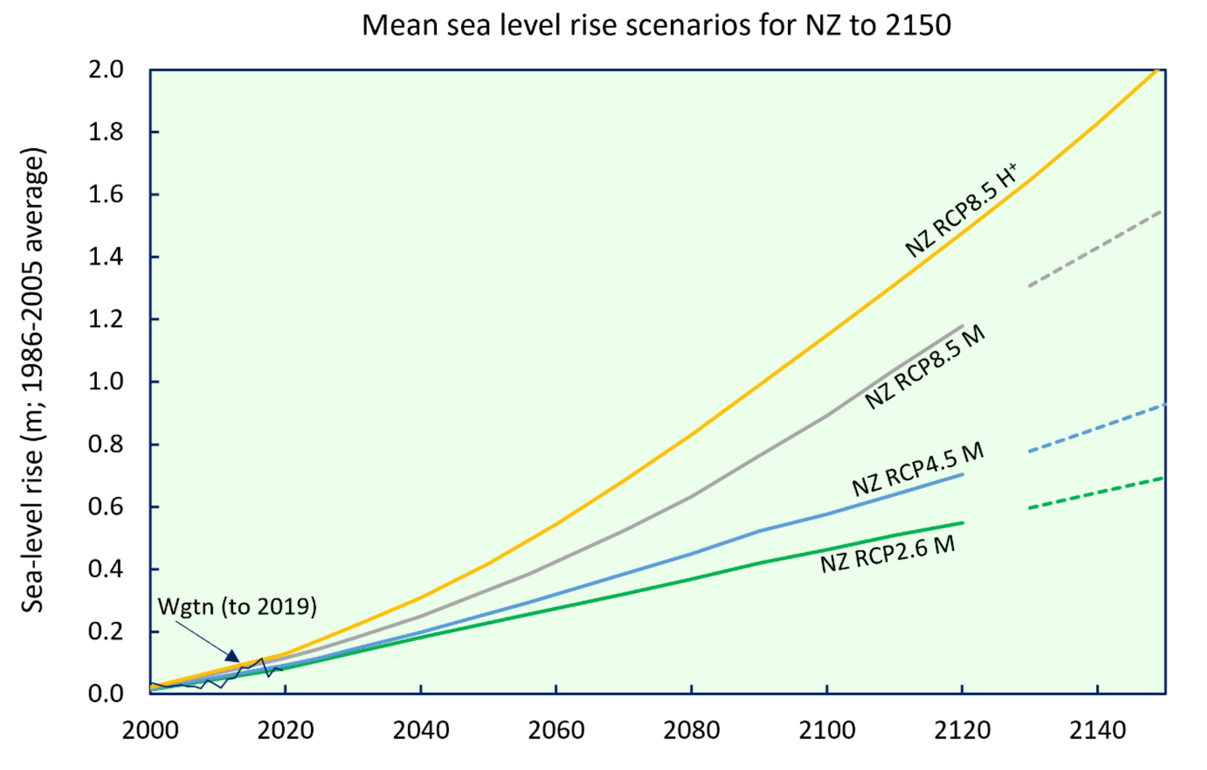


Figure 3-1: The four SLR scenarios for NZ (excluding VLM) from the MfE coastal guidance (MfE 2017) out to 2150 overlain by the annual MSL series from Wellington Harbour for 2000–2019 (bottom panel of Figure 2-1). Note: SLR is relative to the 1986–2005 average MSL (refer Section 3.1.3). *Source*: Projections - MfE 2017, tide gauge data – GWRC.

Table 3-1: The four SLR scenarios for NZ (excluding VLM) from the MfE coastal guidance (MfE 2017). Note: Columns 2, 3, 4: based on IPCC AR5 (Church et al. 2013a); and column 5: NZ RCP8.5 H+ scenario (83rd percentile, from Kopp et al. 2014). Note: M = median; m = metres; To determine the local relative SLR, a further component for persistent vertical land movement will need to be added (subsidence) or subtracted (uplift).

Year	NZ RCP2.6 M (median) [m]	NZ RCP4.5 M (median) [m]	NZ RCP8.5 M (median) [m]	NZ RCP8.5 H+ (83rd percentile) [m]
1986–2005 [1996]	0	0	0	0
2020	0.08	0.08	0.09	0.11
2030	0.13	0.13	0.15	0.18
2040	0.18	0.19	0.21	0.27
2050	0.23	0.24	0.28	0.37
2060	0.27	0.30	0.36	0.48
2070 (50 yrs)	0.32	0.36	0.45	0.61
2080	0.37	0.42	0.55	0.75
2090	0.42	0.49	0.67	0.90
2100	0.46	0.55	0.79	1.05
2110	0.51	0.61	0.93	1.20
2120 (100 yrs)	**0.55**	**0.67**	**1.06**	**1.36**
2130	0.60*	0.74*	1.18*	1.52

* Extended set from 2130 onwards based on applying the same rate of rise of the relevant representative concentration pathway (RCP) median trajectories from Kopp et al. 2014 to the end values of IPCC 5th Assessment Report (AR5) projections.

Table 3-2 lists the RSLR that would occur under the four MfE (2017) scenarios combined with two scenarios of VLM of 1 and 3 mm/yr ongoing subsidence for Wellington, leaving aside any major earthquake rupture events that may or may not occur in the future. Over the next 100-year planning horizon, including VLM at −1 mm/yr subsidence in local RSLR projections adds an additional 0.12 m to ocean SLR by 2120, or an additional 0.37 m by 2120 for ongoing subsidence of 3 mm/yr. The latter is the recommended subsidence to use for the coastal mapping overlay for Wellington City until such time as ongoing monitoring of VLM indicates otherwise (see analysis in Section 2.4).

WCC have elected to use only the top two scenarios from MfE (2017) for this District Plan, that is NZ RCP8.5 M and NZ RCP8.5 H+. Table 3-2 combines these two scenarios with the −3 mm/yr VLM allowance for subsidence. These values are to be used for the coastal inundation + RSLR map overlays for the revision of the District Plan.

Table 3-2: RSLR projections for Wellington City using 4 scenarios from MfE (2017), which do not include VLM, combined with two scenarios (italics) of local VLM (1 and 3 mm/yr subsidence) for selected timeframes. Note: Shading for visual clarity.

Year (+ VLM)	NZ RCP2.6 M (median) [m]	NZ RCP4.5 M (median) [m]	NZ RCP8.5 M (median) [m]	NZ RCP8.5 H+ (83rd percentile) [m]
2040	**0.18**	**0.19**	**0.21**	**0.27**
2040 + 1 mm/yr	*0.22*	*0.23*	*0.25*	*0.31*
2040 + 3 mm/yr	*0.31*	*0.32*	*0.34*	*0.40*
2070 (~50 yrs)	**0.32**	**0.36**	**0.45**	**0.61**
2070 + 1 mm/yr	*0.40*	*0.44*	*0.53*	*0.69*
2070 + 3 mm/yr	*0.54*	*0.59*	*0.67*	*0.83*
2100	**0.46**	**0.55**	**0.79**	**1.05**
2100 + 1 mm/yr	*0.57*	*0.65*	*0.90*	*1.15*
2100 + 3 mm/yr	*0.77*	*0.86*	*1.10*	*1.36*
2120 (~100 yrs)	**0.55**	**0.67**	**1.06**	**1.36**
2120 + 1 mm/yr	*0.67*	*0.79*	*1.18*	*1.48*
2120 + 3 mm/yr	*0.92*	*1.04*	*1.43*	*1.73*

Finally, Table 3-3 demonstrates the effect on planning timeframes for some selected thresholds of RSLR occurring (to the nearest five years) of the trickle-down effect of ongoing landmass subsidence. Essentially, inclusion of ongoing subsidence of, for example 3 mm/yr, advances the time when a specific sea-level rise threshold is reached by around 15–20 years for the NZ RCP 8.5 M scenario, and even further forward by around 20–40 years earlier for the lower-emissions NZ RCP4.5 M scenario.

Such RSLR thresholds are increasingly being used to define localised adaptation thresholds for low-lying coastal areas. For example, an adaptation threshold, when RSLR exceeds say 0.3 m for a specific locality, maybe the pre-agreed point at which intolerable impacts or deterioration of infrastructure services could occur. Such thresholds would emerge from community or iwi/hapū engagement during the dynamic adaptive pathways planning (DAPP) processes. Similar adaptation thresholds can be determined for council or regional infrastructure services, as described in a pilot study for Petone by Kool et al. 2020.

Table 3-3: Approximate timeframes (to nearest five years) when specific RSLR heights would be reached for Wellington City using two scenarios from the national coastal guidance (MfE 2017), which do not include VLM, combined with two VLM scenarios (1 and 3 mm/yr subsidence).

RCP Scenario RSLR increment	Timeframe for: 0 mm/yr subsidence	Timeframe for: 1 mm/yr subsidence	Timeframe for: 3 mm/yr subsidence
	NZ RCP4.5 M		
0.3 m RSLR	2060	2050	<2040
0.5 m RSLR	2090	2080	2060
1.0 m RSLR	2165	2145	2115
	NZ RCP8.5 M		
0.3 m RSLR	2050	2045	2035
0.5 m RSLR	2075	2065	2055
1.0 m RSLR	2115	2110	2095

3.4 RSLR elevations for coastal mapping and assessments

For **Wellington City** (**Harbour and south coast**), add 0.164 m (from Section 3.1.3) to all RSLR projections in Table 3-2 to obtain future RSLR in terms of WVD-53. For future sea level in the newer national vertical datum, NZVD-2016, subtract 0.186 m from all RSLR projections in Table 3-2.

The equivalent offsets for the **west coast (Mākara and Ōhāriu)**, where MSL is setup by an additional 3 cm (Section 3.1.2), are to add 0.194 m to all RSLR projections in Table 3-2 to obtain future levels in WVD-53 and subtract 0.156 m from all RSLR projections in Table 3-2 relative to NZVD-2016.

4 Conclusions

In summary, on the basis of WCC's selection of two RCP scenarios, the 100-year timeframe from NZCPS, and appropriate VLM guidance of using 3 mm/yr subsidence, the elevations of future sea-level to use for the next phase of future coastal flood mapping for the District Plan revision for Wellington City are listed in Table 4-1

Table 4-1: Summary of RSLR projections of future MSL in 2120 for use in coastal flood mapping for the present District Plan revision. Values based on two selected RCP scenarios from MfE(2017) specifically requested by WCC and a -3 mm/yr VLM allowance that both extend out approximately 100-years from now (2120).

Scenario (incl. VLM = 3 mm/yr subsidence)	MSL elevation (relative to 1985–2006 local MSL baseline) [m]	MSL elevation (WVD-53) [m]	MSL elevation (NZVD-2016) [m]
	Wellington Harbour and South Coast		
NZ RCP8.5M (median) + VLM	**1.43**	**1.59** [= 1.43 + 0.164]	**1.24** [= 1.43 - 0.186]
NZ RCP8.5 H+ (83rd percentile) + VLM	**1.73**	**1.89** [= 1.73 + 0.164]	**1.54** [= 1.73 - 0.186]
	West coast (Mākara and Ōhāriu)		
NZ RCP8.5M (median) + VLM	**1.43**	**1.62** [= 1.43 + 0.194]	**1.27** [= 1.43 - 0.156]
NZ RCP8.5 H+ (83rd percentile) + VLM	**1.73**	**1.92** [= 1.73 + 0.194]	**1.57** [= 1.73 - 0.156]

For the west coast areas of Mākara and Ōhāriu, the 3 cm MSL offset from Wellington Harbour (see Section 3.1.2) has been included in Table 4-1.

For stress-testing any coastal provisions of the revised District Plan, in terms of timing for the onset of specific adaptation thresholds, the lower RSLR scenarios from the national guidance should also be considered from Table 3-2 and Table 3-3 for later timing (if effective global emissions reduction occurs) besides the two upper scenarios.

5 References

Begg, J.G., Van Dissen, R.J., Rhoades, D.A., Lukovic, B., Heron, D.W., Darby, D.J., Brown, L.J. (2002) Coseismic subsidence in the Lower Hutt Valley resulting from rupture of the Wellington fault. *Paper number 3621 – Institute of Geological & Nuclear Sciences* (EQC funded project 01/456) - https://www.eqc.govt.nz/research/research-papers/coseismic-subsidence-lower-hutt-valley-rupture-wellington-fault and https://www.nzsee.org.nz/db/2004/Paper43.pdf

Bell, R.G., Hannah, J. (2012) Sea-level variability and trends: Wellington Region. Prepared for Greater Wellington Regional Council by NIWA and Vision NZ Ltd., NIWA Client Report No. HAM2012–043: 74 p. http://www.gw.govt.nz/assets/Climate-change/Sea-Level-Variability-and-Trends-in-the-Wellington-Region2012.pdf

Bell, R.G., Hannah, J. (2019) Update to 2018 of the annual MSL series and trends around New Zealand. NIWA Client Report 2019263WN prepared for the Ministry for the Environment (Publication Ref number: CR 386). 20p. https://www.mfe.govt.nz/publications/marine/update-2018-of-annual-msl-series-and-trends-around-new-zealand

Bell, R.G., Denys, P., Hannah, J. (2018) Update on relative sea-level rise and vertical land motion: Wellington region. NIWA Client Report 2019007HN, prepared for Greater Wellington Regional Council, December 2018, 36 p. https://www.gw.govt.nz/natural-hazards-management-strategy/

Berryman, K., Hull, A. (2003) Tectonic controls on Late Quaternary shorelines: A review and prospects for future research. In: *The New Zealand Coast–Te tai o Aotearoa*, J.R. Goff, S.L. Nichol, H.L. Rouse (Eds.), Dunmore Press with Whitireira Publishing and Daphne Brasell Associates Ltd, Chapter 2: 25–58.

Church, J.A., White, N.J. (2011) Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, 32(4): 585–602. Retrieved from http://dx.doi.org/10.1007/s10712-011-9119-1.

Dangendorf, S., Hay, C., Calafat, F.M., Marcos, M., Piecuch, C.G., Berk, K., Jensen, J. (2019) Persistent acceleration in global sea-level rise since the 1960s. *Nature Climate Change*, 9: 705-710. https://www.nature.com/articles/s41558-019-0531-8

Douglas, B.C. (2001) Sea level change in the era of the recording tide gauge. Chapter 3. In: B.C. Douglas, M.S. Kearney, P.L. Stephen (Eds) *International Geophysics*, 75: 37-64. Academic Press, San Diego. Retrieved from http://dx.doi.org/10.1016/S0074-6142(01)80006-1.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L., Wu, Y.-H. (2020) The causes of sea-level rise since 1900. *Nature*, 584: 393–397. https://doi.org/10.1038/s41586-020-2591-3

Gibb, J.G. (1986) A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. *Royal Society of New Zealand Bulletin*, 24: 377–395.

Hannah, J. (2004) An updated analysis of long-term sea level change in New Zealand. *Geophysical Research Letters*, 31: L03307, doi:10.1029/2003GL019166. https://doi.org/10.1029/2003GL019166

Hannah, J., Bell, R.G. (2012) Regional sea level trends in New Zealand. *Journal of Geophysical Research*, 117: C01004, doi:10.1029/2011JC007591. https://doi.org/10.1029/2011JC007591

Hannah, J., Bell, R.G. (2020) Forensic analysis of the 1944 datum shift at the Wellington tide gauge. *New Zealand Surveyor Journal*, 306 :1–9. Journal of New Zealand Institute of Surveyors. ISSN: 0048-0150. https://www.surveyspatialnz.org/Attachment?Action=Download&Attachment_id=6130

IPCC (2019) *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

IPCC SROCC 2019, Chapter 4 reference: Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R.M., Ghosh, T., Hay, J., Isla, F., Marzeion, B. Meyssignac, B., Sebesvari, Z. (2019) Sea-level rise and Implications for Low-Lying Islands, Coasts and Communities. In*: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

Kool, R., Lawrence, J., Drews, M., Bell, R. (2020) Preparing for sea-level rise through adaptive managed retreat of a New Zealand stormwater and wastewater network. *Infrastructures*, 5, 92. doi:10.3390/infrastructures5110092. https://doi.org/10.3390/infrastructures5110092

Levy, R., Naish, T., Bell, R., Golledge, N., Clarke, L., Garner, G., Hamling, I., Heine, Z., Hreinsdottir, S., Lawrence, J., Lowry, D., Priestley, R., Vargo, L. (2020) Te tai pari o Aotearoa – Future sea level rise around New Zealand's dynamic coastline. p. 11-20. In: C. Hendtlass, S. Morgan, D. Neale (Eds.), *Coastal systems and sea level rise: What to look for in future*. Special Publication 4, NZ Coastal Society, Nov 2020, 68 p. https://www.coastalsociety.org.nz/media/view/publications/sea-level-rise/

McSaveney, M.J., Graham, I.J., Begg, J.G., Beu, A.G., Hull, A.G., Kim, K., Zondervan, A. (2006) Late Holocene uplift of beach ridges at Turakirae Head, south Wellington coast, New Zealand. *New Zealand Journal of Geology and Geophysics*, 49(3): 337–358. https://doi.org/10.1080/00288306.2006.9515172

MfE (2017) Coastal hazards and climate change: Guidance for local government. Bell, R.G., Lawrence, J., Allan, S., Blackett, P., Stephens, S.A. (Eds.), Ministry for the Environment (MfE) Publication No. ME 1292: 284 p + Appendices. http://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government

Steele, C., Williams, N, Dawe, I. (2019) Preparing coastal communities for climate change: Assessing coastal vulnerability to climate change, sea level rise and natural hazards.

Mitchell Daysh Client Report MDL000639, June 2019. https://www.gw.govt.nz/natural-hazards-management-strategy/

Tonkin + Taylor (2013) Wellington City Council: Sea-level rise options analysis. Tonkin + Taylor Client Report 6157, prepared for Wellington City Council. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjEsKWbi4btAhWjpOkKHTu5BioQFjABegQIBBAC&url=https%3A%2F%2Fwellington.govt.nz%2F~%2Fmedia%2Fservices%2Fenvironment-and-waste%2Fenvironment%2Ffiles%2F61579-wcc-sea-level-rise-options.pdf&usg=AOvVaw2P0AQppsQHqDZShErKqqk6