Update to 2020 of the annual mean sea level series and trends around New Zealand

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Contents

Tables

Figures

Executive summary

The purpose of this report is to update the "Coastal Sea-level Rise" (CSLR) indicator that the Ministry for the Environment (MfE) and Stats NZ use within a suite of indices to report on the state of Aotearoa-New Zealand's marine environment under the Environmental Reporting Act 2015. Specifically, MfE have requested this update to the CSLR indicator for inclusion in the upcoming "Our Marine Environment (OME 2022)" report.

This report builds on previous reports to MfE quantifying trends in CSLR up to 2015 (Macara, 2017) and 2018 (Bell & Hannah, 2019), with the former coinciding with the analysis of trends in sea-level rise for the compilation of the 2017 MfE Coastal Hazards and Climate Change guidance for local government (MfE, 2017). The analysis retains the prior methodology to update the CSLR trends through to the end of 2020.

The CSLR indicator represents annual mean sea levels (AMSL) relative to respective baseline mean sea level at six sea-level gauge stations around Aotearoa-New Zealand: Auckland, Wellington, Lyttelton, Dunedin, Moturiki (Mount Maunganui) and New Plymouth (Port Taranaki).

From this data, linear trends and standard deviations are updated, demonstrating changes in mean sea level over time. The Ministry will publish the data and trends resulting from this Report under a CC-BY licence in "Our Marine Environment (OME 2022)" and provide the data and metadata via their website.

AMSL is a measure of the relative rise in sea level at each location, measured relative to the adjacent landmass which is influenced by both vertical land movement (uplift or subsidence) and absolute changes in sea level. If ongoing subsidence occurs, this will locally or regionally exacerbate the rise in mean sea level around Aotearoa-New Zealand (Levy et al. 2020).

All series of AMSL have been normalised to an average mean sea level over the two-decade baseline period 1995-2014 (inclusive), which is the latest reference period used by the Intergovernmental Panel on Climate Change (IPCC). Given the different local survey datums used for the 6 gauges, this normalisation enables a more consistent basis for comparison of relative SLR around Aotearoa-New Zealand. It is also the same zero baseline period used in the MfE interim guidance on the use of new IPCC AR6 sea level projections (MfE, 2022). The duration of the baseline is also long enough (20-years) to cover the range of tidal combinations (18.6 years) and some of the shorter-cycle climate variability (e.g., the El Niño-Southern Oscillation or ENSO).

AMSL was the highest on record for most sites over the period 2016 to 2019 years, while there was a slight decrease across all sites in 2020 due to a mix of climate variability and variations in vertical land movement.

Variations from year to year in AMSL will continue to occur over and above the underlying rise in mean sea level rather than a smooth averaged rising trajectory which is often portrayed in SLR projections.

Inter-year variability is primarily from:

- Climate cycles such as the 2–4-year ENSO cycle and the longer 20–30-year Interdecadal Pacific Oscillation (IPO) as well as annual variability in regional sea-surface height from changes in the seasonal sea temperatures on the continental-shelf.

For instance, around Aotearoa-New Zealand, AMSL is usually higher than "normal" in a lagged response to La Niña episodes (e.g., 2016 to mid-2019), and somewhat lower following El Niño episodes, such as mid-2019 to 2020, which largely explains the slight dip in AMSL during 2020.

- Changes in vertical land movement, such as varying co-seismic and post-seismic land movements as observed in Wellington, Lyttelton and to a lesser degree Port Taranaki from the Kaikōura/North Canterbury earthquake sequence that commenced on 14 November 2016. These changes are further exacerbated by ongoing long term landmass adjustments from inter-seismic activity, such as an underlying subsidence trend in the lower North Island.

Climate change is resulting in an increasing rate of rise in mean sea level around New Zealand that underlies interannual and multi-decadal climate variability. To quantify the increase the four longer sea-level data series were each split into two equal durations of at least 50 years at 1960, i.e. 1901 to 1960 and 1961 to 2020 to capture the full range of underlying sea level rise processes to provide robust trend estimates (as done globally by Church & White, 2011). The average relative SLR rate increased between 1.4 to 2.6-fold for a given site from 1901–1960 to 1961–2020. This pattern of increasing rates of sea-level rise is consistent with global sea level rise trends (e.g., Church and White, 2011, Oppenheimer et al. 2019, Frederikse et al. 2020).

The Port of Lyttelton exhibits the highest relative SLR rate of the 4 longer-term gauge sites, with a rising linear trend of 2.24 ±0.09 mm/yr from 1901 to 2020, increasing to 2.77 ±0.20 mm/yr since 1961. Wellington is next highest with a trend of 2.04 ±0.09 mm/yr from 1901 to 2020, increasing to 2.84 ±0.18 mm/yr post 1961, the highest of all six New Zealand sites analysed. The higher rate in the Wellington region over recent decades is partly due to the underlying inter-seismic subsidence, for which GPS measurements have only been available over the last 10–24 years (Bell et al. 2018, Denys et al. 2020). The lowest rate of relative sea-level rise occurs at New Plymouth (Port Taranaki) although there are caveats on the reliability of the tide-gauge datum (Appendix A and B).

1 Context and Purpose

The purpose of this report is to update the “Coastal Sea-level Rise” (CSLR) indicator that the Ministry for the Environment (MfE) and Stats NZ use within a suite of indices to report on the state of Aotearoa-New Zealand’s marine environment under the Environmental Reporting Act 2015. Specifically, MfE have requested this update to the CSLR indicator for the upcoming “Our Marine Environment (OME 2022)” report. This report builds on previous reports to MfE quantifying trends in CSLR up to 2015 (Macara, 2017) and 2018 (Bell and Hannah, 2019), with the former coinciding with the analysis of trends in sea-level rise (SLR) for the compilation of the 2017 MfE Coastal Hazards and Climate Change guidance for local government (MfE, 2017).

The CSLR indicator represents annual mean sea levels (AMSL) relative to respective baseline mean sea level at six sea-level gauge stations around New Zealand. From this data, linear trends and standard deviations are updated, demonstrating changes in mean sea level over time. The Ministry will publish the data resulting from this Report under a CC-BY licence in “Our Marine Environment (OME 2022)” and provide the data and metadata via their website.

This update reports on the AMSL series with the inclusion of data from the 2019 and 2020 years, relative to the average 1995–2014 mean sea level (baseline), and associated updated trends in CSLR, from long-term sea-level gauge records at six coastal locations: Auckland, Wellington, Lyttelton, Dunedin, Moturiki (Mount Maunganui) and New Plymouth (Port Taranaki).

The methodology used by the authors to update the CSLR series and trends is consistent with that of Macara (2017) and Bell & Hannah (2019), which is provided in detail in Appendix C.

2 Data processing

2.1 Climate data

Climate data, comprising monthly and annual average air temperature and barometric pressure (adjusted to mean sea level), from climate sites listed in Table 2-1 were used as input parameters for determining CSLR trends, using the method outlined in previous journal papers (Hannah 1990, 2004, Hannah & Bell, 2012) and covered in Appendix C.

Table 2-1: List of climate station data from NIWA's CliDB archive used to construct a monthly and annual time series of air temperature and mean sea-level pressure data. Used to process trends from the AMSL time series data for the update for 2019–2020 years. Abbreviations: T = air temperature; MSLP = mean sea level pressure; EWS = Environmental Weather Station; AWS = Automatic Weather Station.

Name	Agent No.	Latitude (deg N)	Longitude (deg E)	Height (m MSL)	Type	Observing Authority
Auckland Aero	1962	-37.0081	174.7887	7	T, MSLP	Airways New Zealand
Christchurch Aero	4843	-43.493	172.537	37	T, MSLP	Airways Corporation
Christchurch Gardens	4858	-43.531	172.619	7	T	Christchurch City Council
Dunedin, Musselburgh EWS	15752	-45.9013	170.5147	4	T, MSLP	NIWA
New Plymouth Aero	2282	-39.012	174.181	27	MSLP	Taranaki Weather Services
New Plymouth AWS	2283	-39.008	174.184	30	T, MSLP	Met Service
Tauranga Aero	1612	-37.6724	176.1964	0	T, MSLP	Sun Air Aviation
Tauranga Aero AWS	1615	-37.673	176.196	4	T, MSLP	Met Service

2.2 Input sea level data and processing to derive annual MSL (AMSL)

Hourly sea-level data from each site has been quality-checked for errors and gaps by John Hannah for five of the gauge records (Appendix A and B) while NIWA has quality-checked the record (from 1974) for Moturiki Island (Mount Maunganui–Mauao) that it operates (previously installed and operated by the Water & Soil Division, Ministry of Works & Development).

The raw data were first plotted and then compared against the predicted tide to better detect data discrepancies including time issues. Obvious errors that had occurred in the original digitising process for earlier pre-digital records and that had been overlooked in the original QA procedures were corrected.

Obvious timing errors that were evidenced in short periods of data were dealt with in two different ways (Hannah, 2004). In the first instance, short spans of data, generally no more than a few days in length, were offset in time to coincide with the predicted tide. In the second instance, longer spans of data showing timing errors were generally left untouched since the effect of such a timing error on any derived monthly sea level mean would be marginal at most. Data that was obviously incompatible with the surrounding record were removed from the record altogether.

As a recent additional quality control measure, a cross-check was undertaken on the LINZ data processing work. Quite unexpectedly, this additional level of audit revealed a problem with the LINZ data extraction software, manifested by truncation of hourly MSL readings of exactly 3000 mm, 2000 mm and 1000 mm to 3 mm, 2 mm and 1 mm respectively (Appendix A). Fortunately, this problem was found to have occurred only occasionally (the exact numbers 3000, 2000 and 1000 occur very rarely) and has typically affected only two annual MSLs for any one port gauge record.

Quality-assurance of the datum levels, the stability of the datum (from benchmarks and GPS measurements) and shifts in datum undertaken by gauge operators, was undertaken by John Hannah (Appendix A), apart from Moturiki Island where the datum is monitored by NIWA field staff. Data showing an obvious datum inconsistency, generally evidenced by a sudden block shift in a portion of the tidal record, were eliminated from the record. There is also a caveat on the quality of the datum for the Port Taranaki gauge (Appendix A and B).

After the quality checks, monthly MSL averages were calculated from the hourly data (if available) for that month. In this analysis, monthly averages were only formed for any month in which at least 50% of the data for that month was available, otherwise left as a blank. The AMSL series were calculated from the calculated monthly MSL values, excluding blank values. For Moturiki, a whole-of-year average was calculated from the hourly data, noting negligible differences (sub mm) by averaging the monthly means over each year.

AMSL values for each specific gauge record were then reduced to a consistent datum throughout each of the time series by applying offsets of both known datum shifts in the data (e.g., a gauge datum re-established when a new gauge was installed or shifted) and the effects of gauge subsidence (e.g., subsidence of the pier the gauge may be attached to relative to hinterland benchmarks). Subsidence of the actual gauge support structure is distinct from local and regional vertical land movement which remains embedded in the time series of CSLR, relative to the adjacent landmass.

The 5-minute or 1-minute sea-level datasets are measured by various port companies (Ports of Auckland Ltd, Port Taranaki, New Plymouth, CentrePort - Wellington, Lyttelton Port Co. Ltd, Port Otago – Dunedin) or NIWA in case of Moturiki. The port datasets are submitted regularly to Land Information NZ (LINZ) as the National Hydrographic Authority and checked before archiving. Although further quality assurance and datum adjustments were undertaken for this report (Appendix A and B) the analysis is reliant on the integrity of the data measured by the port companies and NIWA field staff.

To augment the shorter Port Taranaki and Moturiki Island digital records, archived historic single averaged MSL values were retrieved from the LINZ archive as follows (having been used to establish the respective local vertical datums early last century):

- New Plymouth – single MSL value averaged for the four years from 1918–1921 of 1.771 m (relative to the 1966 Port Chart Datum), placed in year 1920 as the approximate mid-point.
- Moturiki Island – single MSL value averaged for the 4 years 1949–1952 of 1.487 m above Tide Gauge Zero (or 0.0 m Moturiki Vertical Datum-1953), placed in year 1951 as the approximate mid-point (also used in Hannah & Bell, 2012).

3 Updates of Coastal SLR trends

Long-term trends were calculated on the AMSL updated values from 1901 to the end of 2020 by John Hannah of Vision NZ Ltd using the methods outlined in Appendix C, Hannah (1990, 2004) and Hannah & Bell (2012). This report follows essentially the same approach used in previous reports on the trend in CSLR up to the end of 2015 (Macara, 2017) and up to the end of 2018 (Bell & Hannah, 2019).

Except for Wellington, all the processed AMSL data remains on the same datum as used in these previous analyses. However, at Wellington, the AMSL data for 1944 and all prior years has had 0.040 m added to eliminate the unknown datum shift that occurred with the movement and installation of a new tide gauge in 1944 at Queens Wharf (Hannah & Bell, 2020). In previous analyses of the trend at Wellington prior to this report, this datum shift was carried through as an unknown variable to determine internally within the multi-variate least squares solution. Unfortunately, this has created confusion, as the solution technique determines a slightly different "1944 datum offset" as the AMSL series lengthens. A decision was made in 2020 to take this datum shift out of the least-squares analysis, after some technical forensic work to optimise and quantify the size of the datum shift (0.04 m) and then applied it directly to the pre-1945 AMSL data before the trend analysis. This process is fully described in Hannah & Bell (2020).

The analysis to fit trends to the AMSL series included the influence of input parameters for annual average air temperature and barometric pressure anomalies from year-to-year using the climate data extracted from climate stations (Table 2-1). These adjustments are usually very small, usually sub-mm, but have still been applied to the AMSL series from all six sites. The details of the analysis are described in Appendix A and linear trends of CSLR are reproduced in Table 3-1, covering 1901 to 2020 and also for the periods 1901—1960 and 1961—2020 to ascertain change in CSLR rate.

Table 3-1: Linear trends of long-term coastal sea-level rise (CSLR) for six tide-gauge sites. Units in mm/yr together with standard deviations in parentheses. See Appendix A and B for details.

Tide gauge	Data Set Length (Total No. of data-years)	MSL Linear Trend					
		1901-1960		1961 - 2020		1901-2020	
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend
Auckland	1899-2020 (120)	58	1.83 (0.21)	60	2.54 (0.21)	118	1.71 (0.08)
Wellington	1891-2020 (122)	59	1.23 (0.26)	60	2.84 (0.18)	119	2.04 (0.09)
Lyttelton	1901-2020 (108)	48	1.33 (0.25)	60	2.77 (0.20)	108	2.24 (0.09)
Dunedin	1899-2020 (103)	48	0.69 (0.20)	53	1.76 (0.20)	101	1.52 (0.08)
New Plymouth[1]	1920-2020 (67)	-	-	60	1.05 (0.34)	-	-
Moturiki[2]	1951-2020 (48)	-	-	47	2.26 (0.26)	-	-

Notes:
1. A trend at New Plymouth for the period 1961-2020 has been shown. However, this is likely to be quite heavily influenced by the as yet unresolved datum problem that occurred between 1960-1980.
2. At Moturiki, the AMSL series used to calculate the 1961-2018 trend starts in 1974 not 1961. Note: work is underway by NIWA to rescue and digitize gauge charts back to the 1950s, which would provide a considerably longer AMSL series.

The trends presented in Table 3-1 show that the rate of mean sea level rise that underlies the interannual and multi-decadal climate variability around New Zealand is increasing. It is further noted that the rates are relative, based on measurements directly from the sea level gauges and include vertical land movement rather than absolute rise in sea level.

The four longer sea-level data series were each split into two equal durations of at least 50 years at 1960, i.e., 1901 to 1960 and 1961 to 2020 to capture the full range of underlying sea level rise processes to provide robust trend estimates (as done globally by Church & White, 2011). The average relative SLR rate increased between 1.4 to 2.6-fold for a given site from 1901–1960 to 1961–2020. This pattern of increasing rates of sea-level rise is consistent with global sea level rise trends (e.g., Church and White, 2011, Oppenheimer et al. 2019, Frederikse et al. 2020).

The Port of Lyttelton exhibits the highest relative SLR rate of the 4 longer-term gauge sites, with a rising linear trend of 2.24 ±0.09 mm/yr from 1901 to 2020, increasing to 2.77 ±0.20 mm/yr since 1961. Wellington is next highest with a trend of 2.04 ±0.09 mm/yr from 1901 to 2020, increasing to 2.84 ±0.18 mm/yr post 1961, the highest of all six New Zealand sites analysed. The higher rate in the Wellington region over recent decades is partly due to the underlying inter-seismic subsidence, for which GPS measurements have only been available over the last 10–24 years (Bell et al. 2018, Denys et al. 2020). The lowest rate of relative sea-level rise occurs at New Plymouth (Port Taranaki) although there are caveats on the reliability of the tide-gauge datum (Appendix A and B).

4 Updated AMSL time series for coastal SLR

All supplied series of AMSL (in accompanying Excel spreadsheet)[1] were normalised to an average mean sea level over the two-decade baseline period 1995-2014 (inclusive), which is the latest reference period used by the Intergovernmental Panel on Climate Change (IPCC). The six normalised AMSL time series are shown in Figure 4-1.

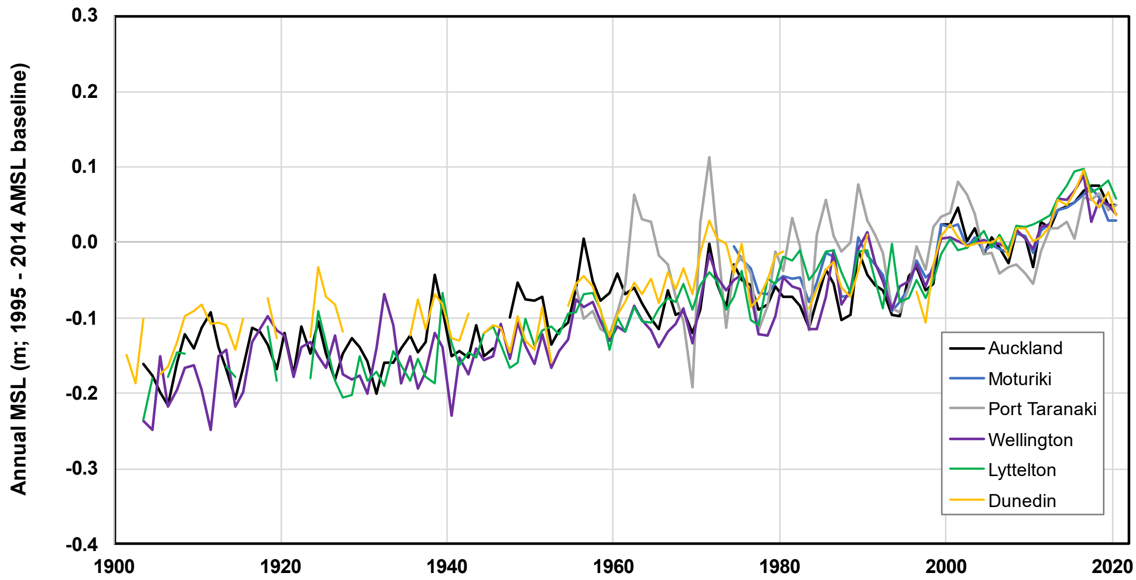

Figure 4-1: Updated AMSL series (to end of 2020) for six long-term gauge sites normalized to the respective 1995-2014 mean sea level.

Given the different local survey datums used for the 6 gauges, this normalisation enables a more consistent basis for comparison of relative SLR around Aotearoa-New Zealand. It is also the same zero baseline period used in the MfE interim guidance on the use of new IPCC AR6 sea level projections (MfE, 2022). The duration of the baseline is also long enough (20-years) to cover the range of tidal combinations (18.6 years) and some of the shorter-cycle climate variability (e.g., the El Niño-Southern Oscillation or ENSO) and variations in vertical land movement.

AMSL was the highest on record for most sites over the period 2016 to 2019 years (Figure 4-1), while there was a slight decrease across all sites in 2020 due to a mix of climate variability and variations in vertical land movement.

Variations from year to year in AMSL will continue to occur over and above the underlying rise in mean sea level rather than a smooth averaged rising trajectory which is often portrayed in SLR projections.

The inter-year variability in AMSL is primarily from:

- Climate cycles such as the 2–4-year ENSO cycle and the longer 20–30-year Interdecadal Pacific Oscillation (IPO) as well as annual variability in regional sea-surface height from changes in the seasonal sea temperatures on the continental-shelf.

[1] *AMSL_6 NZ gauge series to 2020_rel 1995-2014 baseline.xlsx*

For instance, around Aotearoa-New Zealand, AMSL is usually higher than "normal" in a lagged response to La Niña episodes (e.g., 2016 to mid-2019), and somewhat lower following El Niño episodes, such as mid-2019 to 2020, which largely explains the slight dip in AMSL during 2020 (Figure 4-1).

The noticeable jump in AMSL across Aotearoa-New Zealand in 1999-2000 (Figure 4-1) was the response of the SW Pacific Ocean being influenced by a switch to the negative phase of the 20–30-year IPO climate-ocean cycle. A small dip in AMSL would be expected when the IPO switches back to a positive phase sometime in the next decade.

- Changes in vertical land movement, such as varying co-seismic and post-seismic land movements as observed in Wellington, Lyttelton and to a lesser degree Port Taranaki from the Kaikōura/North Canterbury earthquake sequence that commenced on 14 November 2016. These changes are further exacerbated by ongoing long term landmass adjustments from inter-seismic activity, such as an underlying subsidence trend in the lower North Island (Bell et al. 2018, Denys et al. 2020).

5 Acknowledgements

Original 5-minute or 1-minute sea-level datasets were originally measured by various port companies (Ports of Auckland Ltd., Port Taranaki – New Plymouth, CentrePort–Wellington, Lyttelton Port Co. Ltd, Port Otago Ltd. – Port Chalmers) or NIWA (owner of the Moturiki gauge).

Data for this updated report were sourced from Land Information NZ (LINZ) as the National Hydrographic Authority or from NIWA (in the case of the Moturiki gauge).

Climate data (air temperature and mean sea level pressure) were extracted from the Climate Database (CliDB) held by NIWA, with data supplied by the various agencies listed in Table 2-1.

6 Glossary of abbreviations and terms

AMSL	Annual mean sea level (averaged each year from hourly sea-level data to a consistent datum)
CD	Local Chart Datum (typically the level at which the lowest low tide seldom reaches)
CSLR	Coastal sea-level rise indicator (name of indicator reported by MfE/Stats NZ)
ENSO	El Niño-Southern Oscillation (2–4-year climate oscillation of the wider Pacific)
IPCC	Intergovernmental Panel on Climate Change (UN agency)
IPO	Interdecadal Pacific Oscillation (20–30-year climate oscillation of the wider Pacific – last IPO phase shift was in 1999)
LINZ	Land Information NZ
MfE	Ministry for the Environment
MSL	Mean sea level (usually expressed over a period of several years, typically 19-20 years)

7 References

Bell, R.G., Denys, P., Hannah, J. (2018). Update on relative sea-level rise and vertical land motion: Wellington region. NIWA Report 2019007HN prepared for Greater Wellington Regional Council, 36 pp. https://www.gw.govt.nz/assets/Emergencies--Hazards/Sea-Level-Trends-in-the-Wellington-RegionUpdate2018.pdf

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

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. http://dx.doi.org/10.1007/s10712-011-9119-1

Denys. P.H., Beavan, R.J., Hannah, J., Pearson, C.F., Denham, M., Hreinsdottir, S. (2020). Sea level rise in New Zealand: The effect of vertical land motion on century-long tide gauge records in a tectonically active region. *Journal of Geophysical Research: Solid Earth 125*, e2019JB018055. https://doi.org/10.1029/2019JB018055

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

Hannah, J. (1990). Analysis of mean sea level data from New Zealand for the period 1899-1988. *Journal of Geophysical Research 95(B6)*: 12399-12405.

Hannah, J. (2004). An updated analysis of long-term sea level change in New Zealand. *Geophysical Research Letters 31(3)*: L03307. http://doi.org/10.1029/2003GL019166

Hannah, J.; Bell, R.G. (2012). Regional sea level trends in New Zealand. *Journal of Geophysical Research: Oceans 117(1)*: C01004. http://doi.org/10.1029/2011JC007591

Hannah, J., Bell, R.G. (2020). Forensic analysis of the 1944 datum shift at the Wellington tide gauge. *NZ Surveyor 306*. 9 pp. https://www.surveyspatialnz.org/members/Publications/nz_surveyor_journal

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: Hendtlass, C., Morgan, S., Neale, D. (eds.), Coastal systems and sea level rise: What to look for in future. Special Publication 4, NZ Coastal Society, Dec 2020, Dec 2020, ISBN: 978-0-473-55110-0. 68 p. https://www.coastalsociety.org.nz/index.php/media/view/publications/sea-level-rise/

Macara, G. (2017). Updated datasets for atmosphere and climate domain report. NIWA Client Report No. 2017054WN. Prepared for the Ministry for the Environment, 11p. Available from www.mfe.govt.nz

Ministry for the Environment (2022). Interim guidance on the use of new sea-level rise projections. Wellington: Ministry for the Environment.

https://environment.govt.nz/publications/interim-guidance-on-the-use-of-new-sea-level-rise-projections/

Ministry for the Environment (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 Publication No. ME 1292. 284 p + Appendices. https://environment.govt.nz/publications/coastal-hazards-and-climate-change-guidance-for-local-government/

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* [Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Poloczanska, E., Mintenbeck, K., Tignor, M., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M. (eds.)].

Appendix A Updated SLR trends to end of 2020

NZ Wide Sea Level Trends to 31 December 2020

Report to NIWA from Vision NZ Ltd

1. Introduction

This report has been produced in response to a request from NIWA to service their contract with the Ministry for the Environment updating the coastal sea-level rise indicator. Two tasks have been undertaken. Firstly, the sea level trends at the ports of Auckland, Wellington, Lyttelton, Dunedin, New Plymouth, and Moturiki have been updated to the end of 2020. Secondly, the analysis procedures used have been detailed, together with some comments on future analysis options. This second part of the project is covered in a supplementary report.

This work, then, not only extends the sea level trend analyses done in Hannah (2019), but also draws upon the material in Hannah (1990) and Hannah (2004). Additionally, it provides a commentary on recent research surrounding sea level trend analysis models and methods.

2. The Data

With the exception of Moturiki where NIWA were responsible for the provision of monthly MSLs, hourly MSLs were provided for all ports by the Tidal Officer at Land Information NZ (LINZ). The supplementary report describes how these data have been processed.

As a recent additional quality control measure, the author has also acquired the same University of Hawaii sea-level processing package used by LINZ (Caldwell, 2014), and used it to cross-check LINZ's work. Quite unexpectedly, this additional level of audit revealed a problem with LINZ's own data extraction software. It appears that for the last six years the LINZ software, has been truncating hourly MSL readings of exactly 3000 mm, 2000 mm and 1000 mm to 3 mm, 2 mm and 1 mm respectively. While LINZ detected this problem in January this year, the author of this report had not been notified nor had the historical files dating back to 2014 been corrected.

Fortunately, this problem was found to have occurred only occasionally (the exact numbers 3000, 2000 and 1000 occur very rarely) and has typically affected only two annual MSLs at any one port – and then only by between 1 mm - 4 mm (i.e., well within the noise level of the data itself). Furthermore, there is only one tide gauge (New Plymouth) where a significant number of tidal readings reach or exceed 3000 mm - thus protecting us from the worst excesses of the problem. With the exception of New Plymouth, there has been no effect on previously published MSL trends.

At New Plymouth the MSL for 2014 altered from 1.923 m to 1.948 m. As a consequence, the previously published MSL trend to the end of 2018 should be changed from 1.33 ± 0.24 mm/yr to 1.36 ± 0.24 mm/yr. We note, however, that the revised trend sits well within the previously derived standard deviation and thus the change, from a statistical point of view, is of little consequence.

Beyond this problem, no other data difficulties were detected. The sea level data sets for 2019 and 2020 show excellent continuity. For documentation purposes outages are noted in Table 1. These data outages are sufficiently short as to have a negligible effect on the sea level trends.

With the exception of Wellington, all the data remains on the same datum as used in previous analyses. At Wellington, however, the MSL data for 1944 and all prior years has had 0.040 m added so as to eliminate the datum shift that is known to have occurred with the movement and installation of the new 1944 tide gauge (Hannah and Bell, 2020). In previous analyses this datum shift has been carried as an unknown in the multi-variate least squares solution. Unfortunately, for those not familiar with the data set or the analysis technique, this has created confusion. A decision was made to eliminate this confusion by estimating the size of the datum shift and applying it to the pre-1945 MSL data. This process is fully described in Hannah and Bell (2020).

Table 1: Datum Information and Data Outages 2019-2020

	Port					
	Auckland	Wellington	Lyttelton	Dunedin	New Plymouth	Moturiki
Missing Data 2019	Nil	2 days -April	11 days – Jan. 5 days - Feb. 2 days - April 2 days –May	Nil	5 days – Aug 2 days – Dec.	Daily data not supplied. Only gap was 55 min (30Apr). All monthly MSLs were available.
Missing Data 2020	Nil	1-day Sept.	½ day March, May. 4 days – Aug 8 days – Sept 2 days – Nov 1½ days – Dec.	Nil	Nil	All monthly MSLs were supplied.
Datum Information	All MSL data corrected to the pre-1973 TG zero.	All MSL data corrected to the zero of the TG used from 18 Nov. 1944, onwards.	All MSL data corrected to the pre-1940 TG zero.	No ongoing datum corrections required. All data refers to the 1899 TG zero.	All MSL data corrected to the TG Zero used for the 1966 E&V tide gauge.	The Moturiki tide gauge zero (1487 mm) below the Moturiki Vertical Datum 1953 is the reference point for all MSL data

3. Length of Record

In the light of recent publicity around the analysis of the Lyttelton tide gauge (TG) data, it is perhaps warranted to comment briefly upon the length of the TG record required so as to provide a reliable estimate for a long-term MSL trend. This issue is discussed in considerable detail by Douglas et al (2001). They note that as one of two primary factors, record length (preferably 60 years or longer), is of the utmost importance in determining reliable estimates of sea level rise. They noted that record lengths as short as 10 or 20 years were in no case found to be adequate or appropriate due to the contaminating effects of decadal and interdecadal signals that mask the true long-term trend. These signals (ENSO and IPO effects) are very apparent in the New Zealand TG data (Hannah and Bell, 2012). Douglas et al (2001), reckoned record lengths down to 50 years permissible - being an adequate trade-off between record length and the number of reliable global TG records available.

For this reason, the end of 1960 was chosen as the point at which to break the New Zealand sea-level data series into two approximately equal components of at least 50 years, i.e., 1900 (approximately) – 1960, and 1961 – present day. It also follows the work done by Church and White (2011) who, using global data sets reported trends before and after 1960. This, therefore, allows a direct comparison with their results.

The issue of record length has recently been revisited by Royston et al (2018) who provide an excellent summary of relevant studies published over the last decade. Amongst other things, and using satellite altimetry data, they investigate the time it takes for a reliable trend of a given size and given reliability to emerge from the background noise. They call this the time of emergence (ToE). Depending upon the criteria set (statistical certainty and target trend to be detected), a variety of answers can be derived. Furthermore, having established these parameters, they also note the influence of other contributing factors including location, noise model, and the use (or otherwise) of climate indices in the analysis.

While their study is particularly focused on monthly satellite altimetry data, it does provide some clues for TG data analysis. In particular, they note that if climate variability can be included in the assessment, the time taken for a trend to emerge from the residual noise can be reduced by up to two decades. While the issue of TG data is not addressed specifically, one might conclude both from their work and other published results (e.g., Denys et al, 2020) that when reliable annual MSL data are used with more refined analysis techniques, a robust trend (standard deviation of, say, 0.5 mm/yr) should be able be able to be determined with, perhaps, only 40 years of data. It is clear that 15 years of data, for instance, will not produce a reliable result for the trend.

4. RESULTS

The data to the end of 2020 have been processed using the same least squares multi-variate analysis method used previously for national MfE/StatsNZ reporting on trends up to 2018. This is outlined in Hannah (1990) and as described in the Supplementary Report. The results are tabulated in Table 2.

Table 2. Long-Term MSL Trends
(Units in mm/yr together with standard deviations)

Port	Length of Data Set (Total no. of yrs)	MSL Linear Trend							
		1961 -2017		1961 - 2018		1961-2020		Full data set to the end of 2018	Full data set to the end of 2020
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend		
Auckland	1899-2020 (120)	57	2.49 (0.24)	58	2.54 (0.23)	60	2.54 (0.21)	1.67 (0.08)	1.69 (0.08)
Wellington	1891-2020 (122)	57	2.74 (0.20)	58	2.79 (0.19)	60	2.84 (0.18)	1.93 (0.09)	1.96 (0.09)
Lyttelton	1901-2020 (108)	57	2.70 (0.22)	58	2.73 (0.21)	60	2.77 (0.20)	2.21 (0.09)	2.24 (0.09)
Dunedin	1899-2020 (103)	50	1.63 (0.22)	51	1.64 (0.21)	53	1.76 (0.20)	1.48 (0.08)	1.52 (0.07)
New Plymouth[1]	1920-2020 (67)		N/A		N/A		N/A	1.36 (0.24)	1.37 (0.23)
Moturiki[2]	1951-2020 (48)	44	2.36 (0.30)	45	2.38 (0.28)	47	2.26 (0.26)	2.12 (0.23)	2.06 (0.22)

Note: 1. Due to the likely influence of data inconsistencies at New Plymouth from 1960-1980, no 1961-2020 analysis is reported for this port. Also, the previously reported trend to the end of 2018 has been restated from 1.33 mm/yr to 1.36 mm/yr (see earlier discussion).

2. At Moturiki, the data series used to calculate the 1961-2018 trend starts in 1974 not 1961.

Discussion

It is relevant to observe that at nearly every port and for all time periods, the sea level trends continue the upward pattern seen over the last three years. The only exception is at Moturiki, where the latest trend for 1961-2020 has decreased somewhat – possibly arising from a recent uplift in vertical land movement (based on the Papamoa GNSS record of vertical land movement). We note too, the relative shortness in length of the Moturiki TG record.

While these year-to-year changes in and of themselves are not statistically significant, the uniformity of trend across all tide gauges indicates either the influence of a longer period oceanographic feature that has a generally uniform affect around the NZ coast (e.g., the 2-4 year ENSO cycle or the longer period IPO cycle) or some other systematic influence that could be either tectonic or climate related. Current research indicates that the size of the tectonic effect is heavily influenced by local processes (Denys et al, 2020; Levy et al. 2020). Thus some other explanation is required. Given the length of data series at the four main ports in particular, a climatic influence provides the most logical reason.

References

Caldwell, P., (2014). Hourly sea level data processing and quality control software (SLP64 User Manual). http:// *ilikai.soest.**hawaii**.edu/uhslc/jasl/slp64/SLP64_Manual.pdf* .

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. http://dx.doi.org/10.1007/s10712-011-9119-1 .

Denys. P.H., Beavan, R.J., Hannah, J., Pearson, C.F., Denham, M., Hreinsdottir, S. (2020). Sea level rise in New Zealand: The effect of vertical land motion on century-long tide gauge records in a tectonically active region. *J. of Geophys. Research: Solid Earth*, 125, e2019JB018055. https://doi.org/10.1029/2019JB018055

Douglas, B.C., Kearney, M.S., Leatherman, S.P., (2001). *Sea level rise history and consequences*. International Geophysics Series, Vol. 75, Academic Press.

Hannah, J. (1990). Analysis of mean sea level data from New Zealand for the period 1899-1988, *Journal of Geophysical Research*, 95, B8, pp. 12,399-12,405.

Hannah, J., (2004). An updated analysis of long-term sea level change in New Zealand. *Geophysical Research Letters*, 31, L03307.

Hannah, J., (2010). The Difficulties in Using Tide Gauges to Monitor Long-Term Sea Level Change. *FIG XXIV Congress, Sydney, April 2010*. Selected as the FIG Article of the Month for July 2010. Also published by request in the Survey Quarterly (NZ), March,2011 and in Position IT (South Africa).

Hannah, J., (2019). NZ wide sea level trends to 31 December 2018. Report to NIWA from Vision NZ Ltd.

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

Hannah, J., Bell R.G., (2020). Forensic analysis of the 1944 datum shift at the Wellington tide gauge. *NZ Surveyor No.306.*

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: Hendtlass, C., Morgan, S., Neale, D. (eds.), *Coastal systems and sea level rise: What to look for in future*. Special Publication 4, NZ Coastal Society, Dec 2020, Dec 2020, ISBN: 978-0-473-55110-0. 68 p.

Royston, S., Watson, C.S., Legrésy, B., King, M.A., Church, J.A., Bos, M.S., (2018). Sea-level trend uncertainty with Pacific climatic variability and temporally-correlated noise. *Journal of Geophysical Research: Oceans*, *123,*1978-1993. https:/doi.org/10.1002/2017JC013655.

Appendix B Update SLR trends to the end of 2020 – Addendum

NZ WIDE SEA LEVEL TRENDS TO 31 DECEMBER 2020

Report to NIWA and Dept of Statistics from Vision NZ Ltd

1. INTRODUCTION

This report has been produced in response to a request from the Dept of Statistics, via NIWA, to produce the Mean Sea Level (MSL) trends, plus their standard deviations, for the periods 1901-1960, 1961-2020 and 1901-2020. Where data allows, this is to be done for Auckland, Wellington, Lyttelton, Dunedin, New Plymouth, and Moturiki Is.

The processing methodology is to be the same as used in Hannah (2021).

2. THE DATA

The data is exactly as used in Hannah (2021). All necessary details can be found in that report.

3. RESULTS

The results are tabulated in Table 1.

Table 1. Long-Term MSL Trends
(Units in mm/yr together with their standard deviations)

Port	Start and end years of the the complete data set plus total number of years of data	MSL Linear Trend					
		1901 -1960		1961 -2020		1901-2020	
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend
Auckland	1899-2020 (120)	58	1.83 (0.21)	60	2.54 (0.21)	118	1.71 (0.08)
Wellington	1891-2020 (122)	59	1.23 (0.26)	60	2.84 (0.18)	119	2.04 (0.09)
Lyttelton	1901-2020 (108)	48	1.33 (0.25)	60	2.77 (0.20)	108	2.24 (0.09)
Dunedin	1899-2020 (103)	48	0.69 (0.20)	53	1.76 (0.20)	101	1.52 (0.08)
New Plymouth	1920-2020 (67)			60	1.05 (0.34)		
Moturiki[1]	1951-2020 (48)			47	2.26 (0.26)		

Note: 1. At Moturiki, the data series used to calculate the 1961-2020 trend starts in 1974 not 1961.

4. DISCUSSION

When comparing the 1901-1960 trend data with previously published results (Hannah, 2016), the following comments will be useful.

(a) The datasets are of a relatively short length to start with. Deleting all data prior to 1901 further reduces their length thus reducing the strength of the solution. This is exacerbated by virtue of the data problems (typically outages) that tend to occur in the earlier years of the TG record.

(b) The previously reported trend at Wellington for 1891-1960 (cf., Hannah 2016) was 0.72 (0.43) mm/yr. This trend was subsequently revised upwards to 1.00 (0.26) mm/yr once the pre-1944 datum correction was applied (Hannah and Bell, 2021). The new trend of 1.23 (0.26) has been heavily influenced by the removal of the data for the years 1891-1893.

(c) A trend at New Plymouth for the period 1961-2020 has been shown. However, this is likely to be quite heavily influenced by the as yet unresolved datum problems that occurred between 1960-1980.

REFERENCES

Hannah, J., (2016). Historic Sea-Level Rise Trends in New Zealand up to 2015: MFE Coastal Guidance Revision. Final report to NIWA from Vision NZ Ltd

Hannah, J., (2021). NZ Wide Sea Level Trends to 31 December 2020. Final report to NIWA from Vision NZ Ltd.

Hannah, J., Bell R.G., (2020). Forensic analysis of the 1944 datum shift at the Wellington tide gauge. *NZ Surveyor No.306.*

Appendix C Methodology of coastal SLR analysis intended for independent replication

SUPPLEMENTARY REPORT
Report to NIWA from Vision NZ Ltd

In this Supplementary Report, the existing mathematical model and computational techniques used to analyse annual MSL data for linear trends are described in detail. The Appendix to this Supplementary Report outlines recent research on the subject and provides comment on possible improvement options.

1. <u>The Mathematical Model</u>

The fundamental mathematical model used in the MSL trend analysis was first developed in 1988 and reported in Hannah (1990). It accommodated both the shorter length data sets available at that time and the best analysis techniques of the day. It has been used consistently since.

The model was similar to those proposed by Rossiter (1972) and Vanicek (1978) and is given by the equation

$$S(t_i) = C_D + C_L + C_A\,(t_i^2) + C_P\,\Delta P(t_i) + C_T\,\Delta T(t_i) + \sum_{j=1}^{2} A_j cos(w_j t_i - \Omega_j) + R(t_i) \qquad (1)$$

where for some MSL at time t_i [$S(t_i)$], C_D is the datum bias (constant offset); C_L the linear trend; C_A any acceleration to such a trend; $C_P\,\Delta P(t_i)$ and $C_T\,\Delta T(t_i)$ the contribution of variations in mean annual pressure and temperature with respect to their long term trends; A_j and Ω_j the amplitudes and phase lags of the periodic components with frequencies w_j corresponding to the lunar tides with periods of 18.613 years and 8.847 years respectively; and R the MSL residual error. For New Zealand purposes (and for Wellington in particular where an unknown datum offset is thought to have occurred with the new installation of the tide gauge in 1944), the equation was modified to allow for the estimation of two different C_D parameters, one for the period prior to Nov. 1944 and the other for the period after.

The sixth term, can be rewritten as a combination of sin and cosine waves, i.e.,

$A\,cos(wt - \Omega) = a cos\,(wt) + b sin\,(wt)$ in which the coefficients a and b are treated as unknowns.

If this substitution is made for each of the two lunar tides, then the full mathematical model becomes:

$$S(t_i) = C_D + C_L + C_A\,(t_i^2) + C_P\,\Delta P(t_i) + C_T\,\Delta T(t_i) + a_1 cos(w_1 t_i) + b_1 sin(w_1 t_i) + a_2 cos(w_2 t_i) + b_2 sin(w_2 t_i) + R(t_i) \qquad (2)$$

In this equation the terms $\Delta P(t_i)$ and $\Delta T(t_i)$ are calculated from

$\Delta P(t_i) = P(t_i) - P(c_1 t_i + d_1)$ and

$\Delta T(t_i) = T(t_i) - T(c_2\, t_i + d_2)$

Where (c_1, d_1) and (c_2, d_2) are the known coefficients determined from the linear pressure and temperature regressions over the time period of the data. They thus represent the annual variation of the pressure or temperature from their respective linear trend lines over the time period of analysis, thus allowing the removal of some of the intrinsic climate variability. This was an enhancement upon Vanicek (1978) who used *P(mean)* and *T(mean)* in place of their respective regression lines.
While Equation (2) represents a full theoretical implementation of the initial mathematical model, over the years of its use, certain practicalities have become apparent. These are as follows.

Firstly, while one can estimate two datum bias parameters (as has historically been the case in Wellington), it becomes inconvenient and potentially confusing to do this every time a new trend analysis is undertaken. Furthermore, not only do these biases change as the data set changes, but they are highly correlated. Thus, the decision was made to undertake a thorough analysis of the 1944 Wellington datum offset, obtain a best estimate, and fix its value once and for all. With this bias estimated and applied, the end result is a time series of data that is referenced to the same datum. This should eliminate confusion to users of the data who might be unfamiliar with Wellington's history.

Secondly, the acceleration term, C_A is highly correlated with the linear trend C_L and is thus difficult to estimate with any accuracy in a data set where it may be weakly defined. For this reason, we have chosen to break the long-term data sets into two parts and analyse each part independently.

Thirdly, and following from the discussion earlier in this report, it is helpful to remember the importance of length of data set if a robust trend analysis is desired c.f., Douglas et al (2001).

In summary, then, the current implementation of the mathematical model for all New Zealand analyses is given by the equation:

$$S(t_i) = C_D + C_L + C_P\,\Delta P(t_i) + C_T\,\Delta T(t_i) + a_1 cos(w_1 t_i) + b_1 sin(w_1 t_i) + a_2 cos(w_2 t_i) + b_2 sin(w_2 t_i) + R(t_i) \qquad (3)$$

2. The Analysis Technique

A standard, multi-variate, weighted least squares estimation process is used on equation (3). The development of the necessary equations can be found in numerous text books, but typically with varying notation. While the form used here is developed in Uotila (1967), an unweighted version (i.e., a version that assumes homogeneity of data) can be found on p.24 in Gelb (1974).

We begin by assuming that the adjusted observations (L_a) are a function of a set of unknown parameters (X_a), i.e.,

$$L_a = F(X_a)$$

This function may be linearised by taking a first order Taylor series expansion about some set of approximate parameter values (X_0). This results in the equation

$$L_b + V = \frac{\partial F1}{\partial X_a} \,\|_{X_a = X_0}\, (X_a - X_0) + F(X_0)$$

or

$$L_b + V = A\dot{X} + L_0$$

or

$$V = A\dot{X} + L \qquad (4)$$

Where $A = \frac{\partial F1}{\partial X_a} \|_{X_a = X_0}$, $\dot{X} = (X_a - X_0)$, $L_0 = F(X_0)$, and $L = L_0 - L_b$. V is the vector of residual errors arising from the observations L_b.

The least squares minimum variance estimate for these unknown parameters is then determined by minimising the function V^TPV subject to the constraint given by equation (4). In this formulation the matrix P is called the weight matrix and is the inverse of the variance covariance matrix of the observations. In the absence of a knowledge of the explicit correlations between each MSL data point, this matrix is assumed to be a diagonal in the form

$$P = \begin{bmatrix} \frac{1}{\sigma_1^2} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{\sigma_n^2} \end{bmatrix}$$

where σ_1^2 is the variance of the first observation, σ_2^2 the variance of the second observation and σ_n^2 the variance of the n^{th} observation.

Since the mathematical model (equation (3)) is linear, all the parameters to be estimated can be assumed to have initial values of zero. Under these conditions, the parameter solution set (X_a) is given in matrix form by

$$X_a = - (A^TPA)^{-1} A^TPL_b \qquad (5)$$

Here, A is a matrix of partial derivatives given by

$$A = \begin{bmatrix} \frac{\partial S(t_1)}{\partial C_D} & \cdots & \frac{\partial S(t_1)}{\partial b2} \\ \vdots & \ddots & \vdots \\ \frac{\partial S(t_n)}{\partial C_D} & \cdots & \frac{\partial S(t_n)}{\partial b2} \end{bmatrix} = \begin{bmatrix} 1 & \cdots & Sin\, w_2\, t_1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & Sin\, w_2\, t_n \end{bmatrix}$$

and L_b is the vector of observed MSLs. Here we assume that we have *n* observations and a total of eight columns of partial derivatives (one for each parameter).

The variance covariance matrix of the estimated parameters is obtained by normal error propagation techniques and is given by $(A^TPA)^{-1}$. The a posteriori variance of unit weight is given by

$$\sigma_o^2 = \frac{V^TPV}{n-u} \qquad (6)$$

Where the *n-u* is known as the degrees of freedom.

By using equation (6) and comparing the value of σ_o^2 to unity, one is able to assess the goodness of fit of the data to the mathematical model.

3. <u>Quality Control</u>

With the exception of Moturiki all the data used in New Zealand's long term MSL analyses are collected by Port Companies. There are numerous ways in which errors can be introduced into the data, a full summary of which can be found in Hannah (2010). While mathematical quality control techniques can be used to assess the data (some of which are described further below), there is a heavy reliance upon a number of external parties to ensure the data's correctness, consistency and accuracy. The following parties are involved.

1. The Data Collectors (typically the port companies - with the exception of Moturiki where NIWA takes responsibility for the data). The data collectors are responsible for ensuring that the tide gauges are well maintained, calibrated and held to a constant zero datum. Should any of these not occur, we then rely upon their documentation to alert us to any corrections to the data that might need to be made.

2. GNS Science, Otago University, and Land Information NZ LINZ. All three organisations play a part in monitoring and assessing datum changes due to earthquakes and longer-term tectonic motion. This data is supplied to LINZ who then correct the raw hourly MSL data such that it refers to the same absolute zero tide gauge datum. In addition, GNS Science and Otago University monitor the gauges at Auckland, Wellington, Lyttelton and Dunedin for local motion such as wharf subsidence. Historically LINZ has done the same for many of the secondary gauges, although this programme seems to have fallen into arrears in recent decades.

3. The LINZ Tidal Officer. LINZ is not only the repository for all national sea level data but is also the liaison point for overseas organisations that may have an interest in this data. When the data arrives at LINZ it is processed via the University of Hawaii, Tidal Processing package (Caldwell, 2014) and typically stored in annual files of hourly MSL data. At this stage the data (in particular, those from Christchurch, Wellington and New Plymouth) are also corrected for the ongoing datum effects of Lyttelton and Kaikoura earthquake sequences.

The University of Hawaii package is designed to identify short term data inconsistencies. It creates a set of 66 tidal constituents for each gauge and uses these to produce a predicted tide for each year of data collected. This predicted tide is compared with the actual tidal data and the differences examined for any discrepancies.

4. The Author of this Report. Having received the annual data files from the LINZ Tidal Officer, the author applies the known long-term datum corrections to ensure that the entire time series of data for each port refers to the same zero TG datum. In addition, he has recently installed his own version of the University of Hawaii Tidal Processing package to check the data received from LINZ.

REFERENCES

Caldwell, P., (2014). Hourly sea level data processing and quality control software (SLP64 User Manual). http:// *ilikai.soest.**hawaii**.edu/uhslc/jasl/slp64/SLP64_Manual.pdf* .

Douglas, B.C., Kearney, M.S., Leatherman, S.P., (2001). *Sea level rise history and consequences*. International Geophysics Series, Vol. 75, Academic Press.

Gelb, A., (1974). *Applied optimal estimation*, M.I.T Press, Cambridge, MA.

Hannah, J. (1990). Analysis of mean sea level data from New Zealand for the period 1899-1988, *Journal of Geophysical Research*, 95, B8, pp. 12,399-12,405.

Hannah, J., (2010). The Difficulties in Using Tide Gauges to Monitor Long-Term Sea Level Change. *FIG XXIV Congress, Sydney, April 2010*. Selected as the FIG Article of the Month for July 2010. Also published by request in the Survey Quarterly (NZ), March,2011 and in Position IT (South Africa).

Rossiter, J.R., (1972). Sea-level observations and their secular variation, *Phil. Trans. Royal Society, London* A272, pp. 131-139.

Uotila, U.A., (1967). Introduction to adjustment computations with matrices, *Dept. of Geodetic Science*, The Ohio State University, Columbus, OH.

Vanicek, P., (1978). To the problem of noise reduction in sea-level records used in vertical crustal movement detection. *Physics of the Earth and Planetary Interiors*, 17, pp. 265-280.