Update on relative sea-level rise and vertical land motion: Wellington region

Prepared for Greater Wellington regional Council

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Executive summary

In 2012, NIWA and Vision NZ Ltd (J. Hannah) prepared a comprehensive technical report for Greater Wellington Regional Council (GWRC) detailing sea-level variability and long-term trends in the rising mean sea level (MSL) in the Wellington region (Bell & Hannah, 2012). The trends in relative sea-level rise (RSLR) were analysed up to the end of 2011.

NIWA was commissioned to coordinate a multi-agency team to update the analysis of trends in both the MSL and vertical land motion (VLM) in the Wellington region, incorporating sea-level and GPS data up to the end of 2017.

This Report outlines the updated analyses for RSLR and the VLM component and provides links to the recent coastal guidance for local government (MfE, 2017) released by the Ministry for the Environment (MfE) in December 2017.

Relative sea-level rise (RSLR)

Annual MSL for 2016 was the highest on record (0.278 m Wellington Vertical Datum-1953), with a decrease of 60 mm in 2017. Other long-term sea-level records in the North Island showed a slight increase in 2017 compared with 2016, while sites in South Island had a slight decrease. The decrease in annual MSL over 2017 for Wellington Harbour is mostly attributable to the ongoing post-earthquake (post-seismic) uplift, +40 mm to date, following the November 2016 Kaikoura earthquake.

When the trend in the pre-1960 dataset for annual MSL is compared with the trend in the post-1960 dataset, the sea-level trend is significantly different well beyond a 99% confidence interval. Annual MSL in the 57 years since 1960 up to the end of 2017 has been rising at a rate of 2.74 ±0.20 mm/year for Wellington Harbour, relative to the adjacent landmass. The updated longer-term RSLR rate (1900–2017, including years 1891-1893) is 2.28 ±0.15 mm/year.

Comparison of the annual MSL series with the four SLR scenarios in the MfE Coastal Guidance (MfE, 2017) out to 2030, shows that it may be a few decades before it is clear which SLR trajectory Wellington is tracking towards, given the climate and seismic (VLM) variability from year to year that influences annual MSL.

Vertical land motion (VLM)

VLM can be a significant contributor to regional and local SLR, with subsidence of the landmass increasing the RSLR to be adapted to, while uplift reduces the effect of the rising ocean level.

For the greater Wellington region, both the secular (long-term) land motion and coseismic displacements during recent earthquakes show mostly subsidence (range +5 mm to −57 mm). Conversely, the ongoing land motion due to the transient postseismic response following the Kaikoura 2016 earthquake and slow-slip events (up to 1 year in duration) are mostly uplift (range +53 mm to −2 mm).

The net effect is that the subsidence due to the subduction of the Pacific plate under the Australian plate and coseismic displacement to date was mostly cancelled out by the current day Kaikoura earthquake postseismic deformation and the upwards ratcheting effect of the SSEs.

Implications

The updated results for the Wellington region in this Report demonstrate the complexities of VLM in the region and how the background secular (long-term) subsidence can occasionally be punctuated by significant seismic displacements, up or down, from seismic processes.

While it is possible to estimate the secular (long term) subsidence and estimate with less certainty the rates of land motion from slow-slip events; it is not possible to estimate the land movement of future earthquake events, and therefore is difficult to incorporate into long-term land-use planning for RSLR.

However, the dynamic adaptive pathways planning (DAPP) approach adopted in 2017 MfE Coastal Guidance can also cover the uncertainty posed by unknown future seismic VLM. The DAPP process maps out alternative pathways or adaptation options, and then monitoring progress towards pre-defined triggers (or decision points) before switching pathways for a coastal area. Monitoring (e.g., number of damaging floods, SLR reached, insurance withdrawn etc.,) and reviewing the situation over the intervening time are crucial elements of this adaptive approach so that the switch to another pathway is undertaken in a timely manner—not too early, and not too late.

Therefore, the "monitor and review" step in the DAPP approach, lends itself to the complexity exhibited in the VLM time series to date in Wellington region and what the future might hold. For example, if secular trend in VLM changes substantially or there is another major earthquake event, then the switch to the next pre-planned adaptation pathway could be delayed or brought forward considering the changes in VLM, as well as the other factors/indicators including SLR and other risk indicators.

The results in this report highlight the critical role of monitoring both VLM via the Global Navigation Satellite System (GNSS) and annual MSL in the Wellington region and the urgent need nationally to bolster long-term GNSS monitoring systems. Specifically, the key need is in coastal areas—especially actively tectonic areas or those urban or peri-urban areas subject to ongoing subsidence from non-tectonic processes (e.g., sedimentary basins such as former river deltas, groundwater pumping, and large-scale drainage networks in low-lying areas). LINZ currently are coordinating efforts to investigate the co-location of several existing sea-level gauges in New Zealand with GNSS monitoring to improve the coverage of VLM measurements (compared with the extensive GeoNet network which is focused on tectonic effects).

Finally, the previous recommendation (Bell & Hannah, 2012) to update the analyses of RSLR and VLM at 5-yearly intervals is justified by the findings of this report and should continue at similar intervals, with a more rigorous assessment undertaken every 10 years.

1 Context and Brief

In 2012, NIWA and Vision NZ Ltd (J. Hannah) prepared a comprehensive technical report for Greater Wellington Regional Council (GWRC) detailing sea-level variability and long-term trends in the rising MSL in the Wellington region (Bell & Hannah, 2012). The trends were analysed up to the end of 2011.

NIWA has been commissioned to coordinate an updated analysis of trends in both the mean sea level (MSL) and vertical land motion (VLM) in the Wellington region, incorporating sea-level and GPS data up to the end of 2017. The multi-agency project team comprised:

- NIWA (Dr Rob Bell): Project Manager and report editor.
- Vision NZ Ltd (Emeritus Professor John Hannah): updated MSL trends.
- School of Surveying, University of Otago (Dr Paul Denys): updated VLM trends and variability.

This report outlines the updated analyses for trends in sea-level rise and VLM over the past two decades and provides links to the recent coastal guidance for local government (MfE, 2017) released by the Ministry for the Environment (MfE) in December 2017.

1.1 Definitions

There are two aspects to determining the rate at which sea level is rising at a location:

1. Calculating the average or mean sea level (MSL) for each year from sea-level gauge measurements (typical 1 or 5-minute intervals) and constructing a time series of annual MSL. MSL is measured relative to a specific vertical datum. For Wellington Harbour, the gauge measures sea level relative to Chart Datum for navigational purposes, which is defined by the height of the gauge zero below a specific benchmark (LINZ, 2018; p. 35). But MSL can also be converted to other datums e.g., the Wellington Vertical Datum–1953 (WVD-53), which is typically used for land-based surveying.
2. Fitting a trend through the annual MSL time series to calculate the long-term trend, which is average rate of change in mm/year of sea level or more commonly referred to generically as sea-level rise (SLR). Note: the rate of change is not tied to a datum.

There are also two ways of expressing SLR:[1]

a. Absolute or eustatic SLR is the rise in sea level relative to the centre of the Earth and is essentially the actual rate of rise in ocean water level. It is measured by altimeters on board satellites, with orbits measured relative to the centre of the Earth.

b. Relative sea-level rise (RSLR) is the local SLR, which includes both the absolute SLR plus changes (up or down) in land elevation for the relevant coastal area. RSLR is determined from tide gauge measurements, as the gauge is subject to both changes in ocean level as well as VLM. It is RSLR that communities need to adapt to.

The schematic in Figure 4-1 shows the makeup of RSLR for a local situation where long-term land subsidence is occurring.

[1] https://www.niwa.co.nz/natural-hazards/hazards/sea-levels-and-sea-level-rise

2 Recap on past trends and rationale for the update

The key findings from the previous report (Bell & Hannah, 2012) were:

- The Wellington region is situated astride a complex network of faults associated with the convergence of the Australian and Pacific crustal plates some 20–40 km beneath the surface. As such, the region has a more complicated spatial and temporal pattern of long-term RSLR than other stable parts of New Zealand.
- Over the decade up to 2011, Wellington City has been subject to recent slow-slip events that have produced an average subsidence of 1.7 mm/year since 2000. Subsidence from GPS records varied across the Wellington region from subsidence of around 1 mm/year on the Kāpiti coast up to between 2–3 mm/year along the Wairarapa coast.
- Month-to-month variability in MSL ranged from -0.16 to +0.20 m after the linear trend in RSLR was removed for the period 1945 to 2011. A higher than normal sea level occurs during La Niña episodes, which are intensified during the negative phase of the longer 20–30-year climate cycle called the Inter-decadal Pacific Oscillation (IPO). Conversely, monthly sea levels are lower than normal during El Niño episodes and the positive phase of the IPO. Currently (since 1999), the IPO has been in a negative phase.
- Wellington Harbour experienced an average rate of RSLR of 2.03±0.15 mm/year, or 0.2 m in the last 100 years up to 2011, which is relative to the inner-city landmass. The rate had increased substantially since earlier assessments by Hannah (1990, 2004) obtained average rises of 1.73 mm/year up to 1988 and 1.78 mm/year up to 2001. However, most of this apparent acceleration is due to slow-slip events from tectonic processes under Wellington city since around 1997 that have produced vertical land subsidence of 1.7 mm/year in the decade 2000–2011 and the influence of an upwards shift in ocean level in 1998–2000 when the Pacific-wide IPO switched to the negative phase.
- It was recommended that on-going monitoring of both relative sea level at Wellington Harbour, and VLM at continuous GPS sites around the city and region, are updated every 5 years with a more rigorous assessment undertaken every 10 years.

This updated report addresses that recommendation.

3 Trend in relative sea-level rise

3.1 Sea-level data and processing

This updated analysis builds on the work undertaken for the MfE Coastal Guidance (MfE, 2017; Chapter 5) and the associated report Hannah (2016), where the trend in the Wellington Harbour gauge record was calculated up to the end of 2015.

As with Hannah (2016), the raw hourly sea-level data for the Queens Wharf gauge (Wellington Harbour) for 2016 and 2017 were provided by the Tidal Officer at Land Information NZ (LINZ), which are in turn supplied to LINZ by GWRC who operate the gauge. While the sea level data set for 2017 is complete, the data set for 2016 is missing eight days of data in November. This has had no significant effect on the outcome of the analysis.

Hourly sea-level data from each site was quality-checked for glitches and gaps. The raw data were first plotted and then compared against the predicted tide to better detect data discrepancies including time issues.

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 best.

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 (Vision NZ Ltd). Data that evidenced an obvious datum inconsistency (generally evidenced by a sudden block shift in a portion of the tidal record) were eliminated from the record.

After the quality checks, Monthly MSL averages were calculated from the hourly data (if available) for each month using the University of Hawaii sea level processing software (Caldwell, 2014). In this analysis monthly averages were only formed for any month in which at least one half of the data for that month was available – otherwise left as a blank. Annual MSL were calculated from the Monthly MSL values (leaving aside blank values).

Annual MSL values for the gauge record were then reduced to a consistent datum throughout the time series (i.e., used the pre-1945 datum for the trend analysis) by applying a datum shift of −316 mm to the annual MSL from 1945 onwards to account for a datum correction of −1.0 feet (between the pre-1945 and the recent pre-Kaikoura earthquake Chart Datum), plus accumulated wharf subsidence of 11 mm in the intervening period to account for differential settlement (relative to the adjacent landmass) of the pier on which the sea-level gauge is mounted.

Localised long-term settlement of the pier that actual gauge support structure sits on is distinct from the wider local and regional VLM, which remains intact in the annual MSL time series as a record of RSLR (i.e., sea-level change relative to the adjacent landmass).

3.2 Annual MSL series (Wellington Harbour)

The annual MSL series for Wellington Harbour is shown in Figure 3-1 in terms of Wellington Vertical Datum–1953 (WVD-53).[2] This regional datum is still commonly used for levels related to land-based activities, defined by 14-years of non-contiguous sea-level measurements collected between 1909 and 1946 (Hannah & Bell, 2012), with that period shown by the dotted line in Figure 3-1. The average MSL over the 1986–2005 period was 0.164 m WVD-53, which is the baseline period used to anchor the Intergovernmental Panel on Climate Change (IPCC) projections and those in the MfE Coastal Guidance (MfE, 2017).

More recently in 2016, a nation-wide vertical datum, the New Zealand Vertical Datum–2016 (NZVD2016) was established by LINZ to provide nation-wide consistency in land elevations. Figure 3-2 shows the equivalent annual MSL time series for Wellington Harbour relative to NZVD2016, which is 0.353 m above WVD-53 (i.e., offset by subtracting 0.353 m).

The annual MSL for 2016 was the highest on record (0.278 m WVD-53), with a decrease of 60 mm in 2017. Other long-term gauge series in the North Island showed a slight increase in 2017 compared with 2016, while sites in South Island had a slight decrease. The decrease in annual MSL over 2017 for Wellington Harbour is mostly attributable to the ongoing post-earthquake (postseismic) uplift, +40 mm to date, following the November 2016 Kaikoura earthquake, as discussed in Section 4.6.

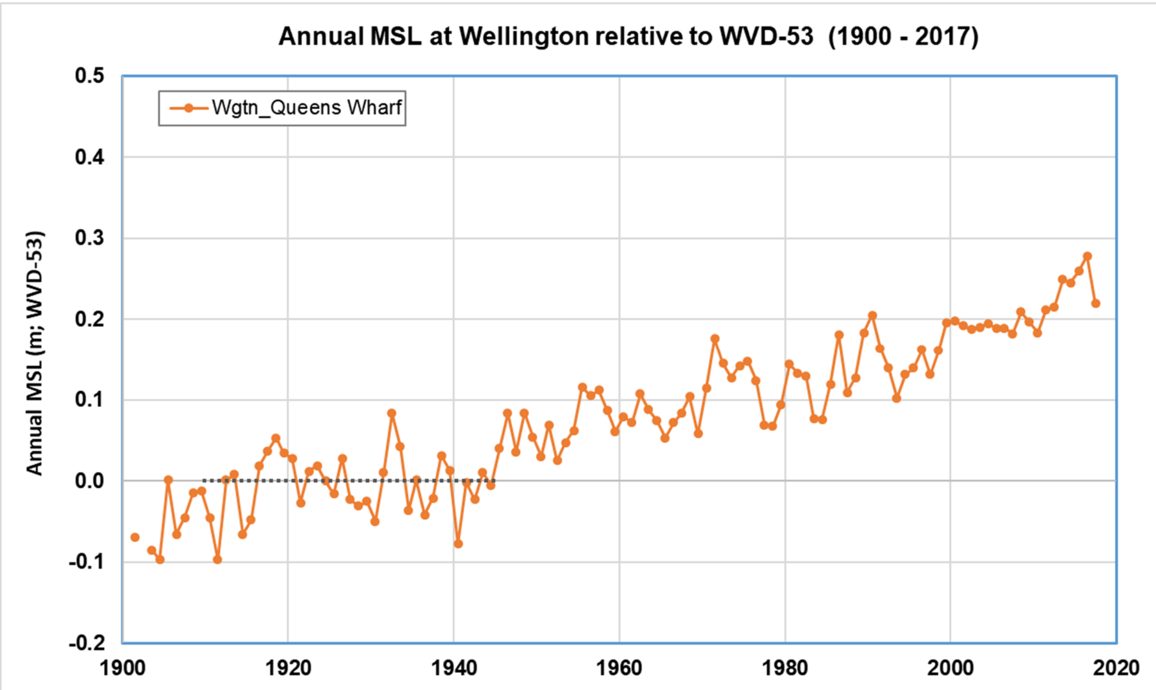

Figure 3-1: Annual MSL series up to end of 2017 for Wellington Harbour (based on Queens Wharf gauge data) relative the WVD-53. Note: WVD-53 is 0.915 m above Chart Datum (pre-Kaikoura earthquake) and the dotted line is the period from which the zero of the regional datum was derived.

[2] Excludes the recent January 2018 change of 27 mm to Chart Datum (LINZ, 2018) following the ongoing response to the November 2016 Kaikoura/North Canterbury earthquake, because insufficient MSL data has been collected to determine the offset and hence conversion to WVD-53.

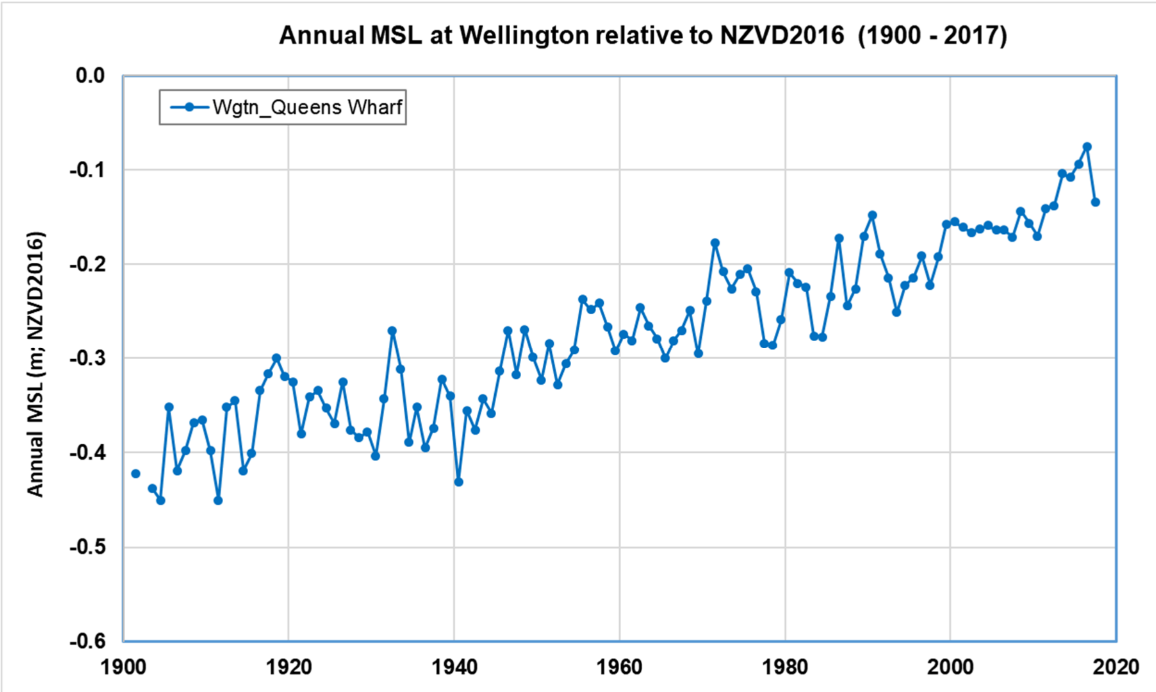

Figure 3-2: Annual MSL series up to end of 2017 for Wellington Harbour (based on Queens Wharf gauge data) relative the NZVD-2016. Note: Offset of -0.353 m applied to series above for WVD-53.

Figure 3-3 overlays the annual MSL time series (relative to the average MSL over the period 1986–2005) with the four SLR scenarios in the MfE Coastal Guidance (MfE, 2017) out to 2030. The comparison shows that it may be a few decades before it is clear which RSLR trajectory Wellington is tracking towards, given the climate and seismic (VLM) variability from year to year.

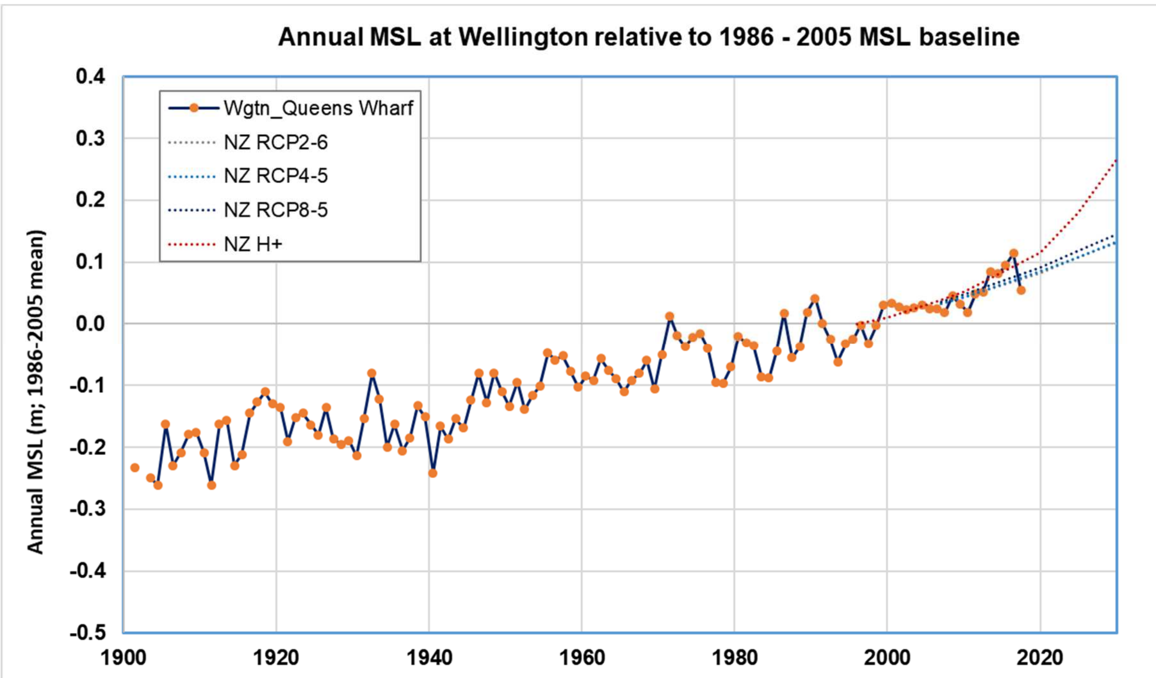

Figure 3-3: Annual MSL series for Wellington Harbour (relative to 1986-2005 average) with the four MfE (2017) SLR scenarios to 2030. Note: the 1986-2005 baseline is used by IPCC for anchoring SLR projections.

3.3 Relative sea-level rise (Wellington Harbour)

As was the case in Hannah (2016) and MfE (2017; Table 7), the annual MSL time series at Wellington were analysed for RSLR trends using three different datasets; that is, the full data set, the start of the data set to 1960, and then the more recent data from 1961–2017.

Two reasons exist for this 1960 split into subsets:

- First, it generally follows the analysis of global data sets of Church & White (2011) using a full record and a post-1960 sub-set, thereby allowing direct comparison with their results.
- Secondly, it allows the linear RSLR trend determined for the first part of the 20th century to be compared with the trend over the last five-and-a-half decades, which almost splits the records in half, as shown in Table 7 of MfE (2017). The gauge data set is approaching a length that should enable this change in trend to be determined over the split record with some confidence (MfE, 2017).

The updated trends in RSLR are shown below in Table 3-1, including the latest annual MSL data to the end of 2017 (updating the trend analysis to 2015 in MfE(2017)).

When the pre-1960 dataset is compared with the post-1960 dataset, the sea-level trend is significantly different well beyond a 99% confidence interval. Annual MSL in the 57 years since 1960 up to the end of 2017 has been rising at a rate of 2.74 ±0.20 mm/year (Table 3-1). The updated longer-term rate of RSLR from 1900–2017 (including the 3 years 1891-1893) is 2.28 ±0.15 mm/year.

It is RSLR, the measured rate of sea-level change by the gauge (relative to the landmass) and future acceleration of that regional/local rate, that will need to be adapted to.

An updated estimate for Eustatic^{TC} SLR (corrected only for VLM due to tectonic subsidence)[3] is included to illustrate the rise in ocean level without VLM (Table 3-1), using an assumed average rate for VLM subsidence of 1.8 mm/year since 1998, when GPS monitoring began. The 1998 date directly affects the result. If this rate of subsidence were to have started prior to 1998 (before GPS monitoring) then the Eustatic^{TC} trend would reduce commensurately with the additional number of years the subsidence was active.

Table 3-1: Long-term trends in RSLR for Wellington Harbour. Units in mm/year with standard deviations in parentheses. The overall annual MSL record is available for years 1891–1893,1901, 1903–2017.
Source: J Hannah, Vision NZ Ltd.

Port: Queens Wharf Wellington	Total length of data set for annual MSL	MSL Linear Trend				
		Start of data set to 1960		1961–2017		Full data set to end of 2017
		Yrs of data	Trend	Yrs of data	Trend	
Relative SLR (RSLR)	119 yrs	62	0.72 (0.43)	57	2.74 (0.20)	2.28 (0.15)
Eustatic^{TC} SLR	*119 yrs*			*57*	*2.22 (0.19)*	*1.98 (0.14)*

Note: Eustatic^{TC} refers to the Wellington data adjusted for net VLM at an assumed rate of 1.8 mm/year since 1998.

[3] Postseismic uplift associated with the 2016 Kaikoura earthquake sequence has not been included in the Eustatic^{TC} SLR correction, having already been applied directly to the hourly sea-level data by LINZ as a datum adjustment. Note: There are also other adjustments to derive eustatic SLR from a gauge record that are not included – the main purpose to show the local influence of VLM.

The Wellington Harbour record exhibits the highest RSLR rate in New Zealand for long-term (>45-year) sites due to the higher subsidence present in the lower North Island (certainly within the last few decades), with Lyttelton the next highest (RSLR of 2.19 mm/year up to the end of 2017).

4 Vertical land motion (VLM) in the Wellington region

4.1 Background

VLM can be a significant contributor to regional and local SLR, more so for subsidence of the landmass, which increases the RSLR to be adapted to (Figure 4-1), while uplift reduces the effect on coastal land of the rising ocean level (absolute SLR).

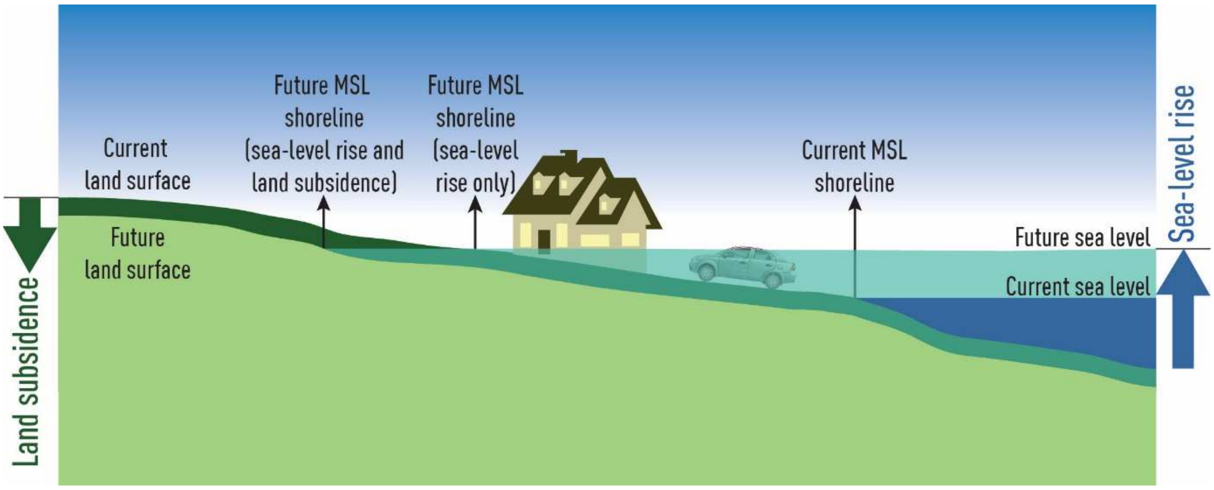

Figure 4-1: Difference in MSL shoreline between absolute and local (relative) sea-level rise where land subsidence occurs. *Source*: NIWA, after Figure 16, MfE (2017).

VLM in the Wellington region has been measured using continuous GPS/GNSS[4] (cGPS, cGNSS) for over 20 years. From 2004, the number of cGNSS sites increased significantly with the establishment by GeoNET of over 100 sites along the east coast of the North Island to monitor the Hikurangi subduction zone. This report utilises over 26 of these sites in the lower North Island and Upper South Island.

In general, the Wellington region is subsiding at rates of between 2–5 mm/year. However, this subsidence is offset by Slow Slip Events (SSE) that periodically uplift the region by as much a 1 mm/year (averaged over 20 years). In addition to these ongoing subduction zone processes, the region has been displaced by recent large earthquake events. Coseismic deformation during events has created subsidence of up to 40 mm while the postseismic displacement has caused uplift of up to 50 mm. Note that the postseismic displacement is an ongoing adjustment process that will contribute more uplift (or subsidence), albeit at a decreasing rate, for the foreseeable future.

While it is possible to estimate the secular subsidence (long term) and estimate with less certainty the SSE rate; it is not possible to determine the displacement of future earthquake events.

4.2 GNSS position time series analysis

4.2.1 GNSS positioning

The data used for this analysis comes from the national networks of continuous GNSS (cGNSS) receivers operated by GeoNET to monitor both regional and national deformation. This includes

[4] System of satellites to provide autonomous geo-spatial positioning. **GNSS** stands for Global Navigation Satellite System and is the standard generic term for satellite navigation systems that provide global coverage. This term includes e.g., the GPS, GLONASS, Galileo, Beidou and other regional systems. **GPS** is the United States system, which is the most utilized satellite navigation system.

receivers in the PositioNZ (LINZ), GeoNET (natural hazard) and tide gauge networks. As the GNSS receivers operate continuously, the networks also accurately measure the displacements due to plate motion, as well as events of a seismic nature e.g., earthquakes and slow slip events (SSEs).

The GNSS data used in this study is processed together with other GNSS sites in New Zealand, Australia, the Pacific and Antarctica. This provides a reliable connection to the International Terrestrial Reference Frame (ITRF), which is currently the most stable global coordinate reference available. We use the most recent and precise GNSS data products available to correct and reduce measurement errors. These include:

- Coordinates: ITRF2014.
- Orbits: CODE precise satellite orbits and clock parameters.
- Ionosphere: Dual frequencies (L1, L2).
- Troposphere: Global Mapping Function.
- Ocean Loading: FES2004.
- APC model: I14.ATX absolute GNSS receiver and satellite model.

The GNSS data was processed using the Bernese software package (v5.2) [Dach et al. 2015], to generate 24-hour daily position solutions. The daily solutions for each GNSS site are used to create a three-dimensional position time series—of which the vertical component is the main interest for VLM.

4.2.2 Position time series analysis

We use a Matlab position time series (`pts`) script developed by Otago University (OU) to model the east, north and height (E, N, H) components of the position time series. Assuming the GNSS site is only affected by steady-state tectonic plate motion, then the model of the position (E, N, H) time series is a simple velocity term. Hence

Equation 4-1: Change in horizontal and vertical land position expressed as a velocity over a period. .

$$\mathrm{X}(t) = V_X(t - t_0)$$

where $\mathrm{X}(t)$ is the coordinate component (i.e., E, N, H) for time t, V_X is the coordinate component velocity, t the time of the observations and t_0 is a (arbitrary) reference time. As an example, the position time series for the Otago University GNSS site (OUSD) is shown in Figure 4-2. Clearly the horizontal velocities ($V_E = -32\ mm/yr$, $V_N = 31\ mm/yr$) are significant and the site has moved horizontally approximately 1 m over 23 years. In contrast, the vertical velocity, $V_H = -1.6\ mm/yr$, is significantly smaller and shows that there has been net VLM of approximately 20 mm for the same period, but with considerable variability.

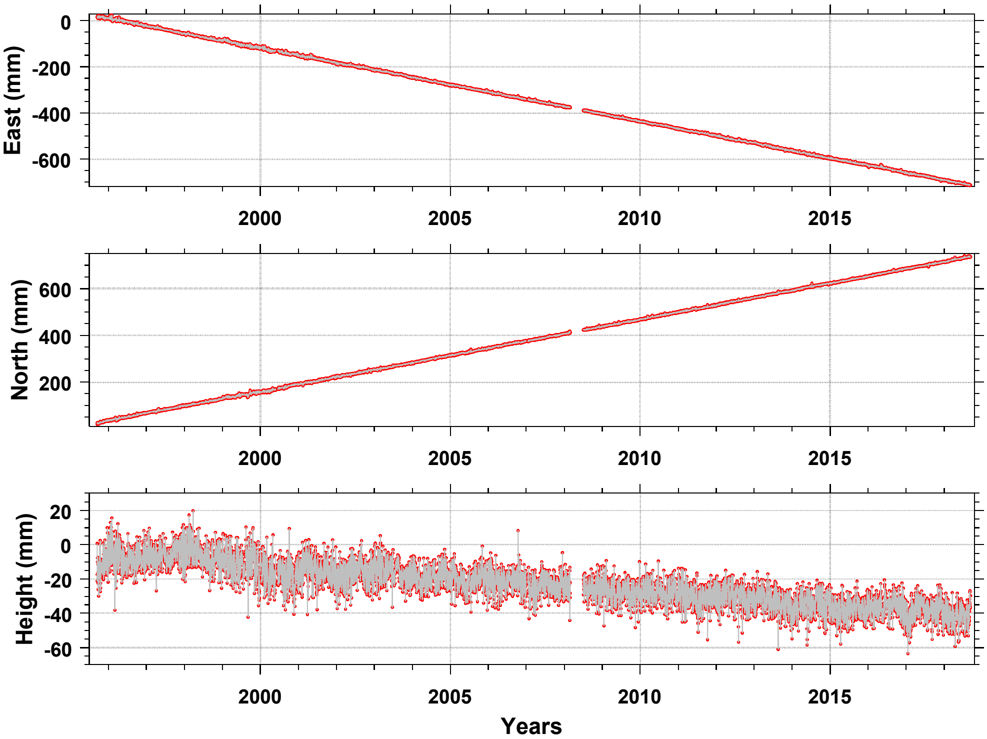

Figure 4-2: An example of a position time series for the cGNSS site at Otago University (OUSD). *Source:* P Denys (Univ. of Otago).

Position time series analysis often needs to consider small displacements, motions and trends. To do this, the long term or secular (linear) trends are removed and the detrended time series is plotted (see Figure 4-3).

From Figure 4-3, the horizontal time series data are more precise than the vertical by a factor of 3–4 times (typical). In general, the horizontal trends will not be considered in this report.

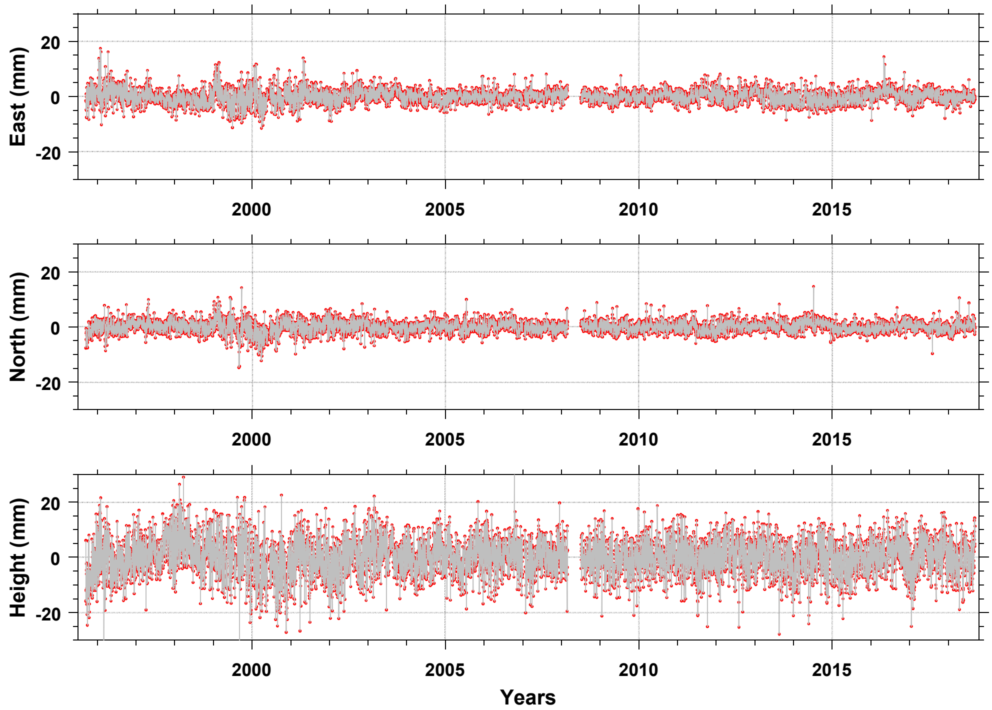

Figure 4-3: Detrended position time series using the same data as in Figure 4-2. *Source:* P Denys (Univ. of Otago).

To accurately model the motion of a site, other effects need to be considered. Detailed modeling of GNSS position time series, included the mathematical expressions, can be found in Denys and Pearson (2015, 2016). Standard model parameters that are routinely included are:

- **Equipment Changes**: When the GNSS equipment is changed such as the receiver and/or antenna, either because the equipment has failed or during routine equipment upgrade, a jump the time series is observed. This is modelled as an offset.
- **Seasonal Effects**: Sites typically display a seasonal motion, which is modeled as annual and semi-annual periodic trends.

Offsets due to changes in the GNSS equipment and cyclical seasonal motion are easily modelled since the exact time of the equipment change is known and the period of seasonal terms (1 year and 6 months) are also assumed.

In tectonically active regions, as in New Zealand, the GNSS sites are affected by seismic activities of various forms. Modelling these motions can be challenging. Broadly, the seismic events are modeled in the following categories.

- **Periodic seismic events**: These are characterised as Slow Slip Events (SSE) that repeat at reasonable regular intervals. The repeat period may be every 18–24 months (e.g., east coast of the North Island, Napier and Gisborne), or over intervals of 5–8 years (e.g., Kāpiti coast).
- **Coseismic deformation**: An earthquake event typically displaces the Earth's crust almost instantly over a period of time from a few seconds to minutes. This creates an offset in the position time series that may be a few millimetres to metres in size (e.g.,

the Kaikoura 2016 earthquake) and is modelled as an offset. (This is identical to an equipment change offset).

- **Postseismic deformation**: If an earthquake event is sufficiently large (typically > Mw 7), then the trajectory of the Earth's crust can respond differently for a period of time following the event. The length of time that the postseismic motion occurs will vary depending upon the size of the earthquake, but can be for a few days, weeks, months or several years.
- **Decay**: Postseismic decay is modelled as a decay function such as logarithmic, exponential or power law. These functions require a decay constant that needs to be determined a priori. Depending upon the nature of the earthquake, postseismic decay represents after slip or relaxation of the crust.
- **Transient velocity**: This is a change in direction and speed (i.e., velocity) following the earthquake for a period after the earthquake.

4.3 GNSS data

The cGNSS data used for this project includes sites in the lower North Island and upper South Island. The time series figures in this report largely depict the GNSS sites close to the coastline of the lower North Island, however, most of the horizontal plots include all sites in both the lower North Island and upper South Island to provide the wider context.

Figure 4-4 depicts the data available and used for this project.[5] The three longest record sites are WGTN (Airport), WGTT (Te Papa) and PAEK (Paekakariki) that were established by GNS Science and OU (1995–2000). Sites established in 2003–2004 (MAST/WRPA, NLSN, GLDB,) were commissioned by LINZ as part of the PositioNZ network. The remaining sites are GeoNet sites that were established to monitor the subduction of the east coast of the North Island and top of the South Island.

The site in the Wairarapa (MAST) has been replaced by a new site (WRPA). These two sites are in close proximity and have been processed as a single site (collocated) in order to extend the time period from 2003–2018.

[5] Map of GNSS sites within GEoNet: https://www.geonet.org.nz/data/network/sensor/map

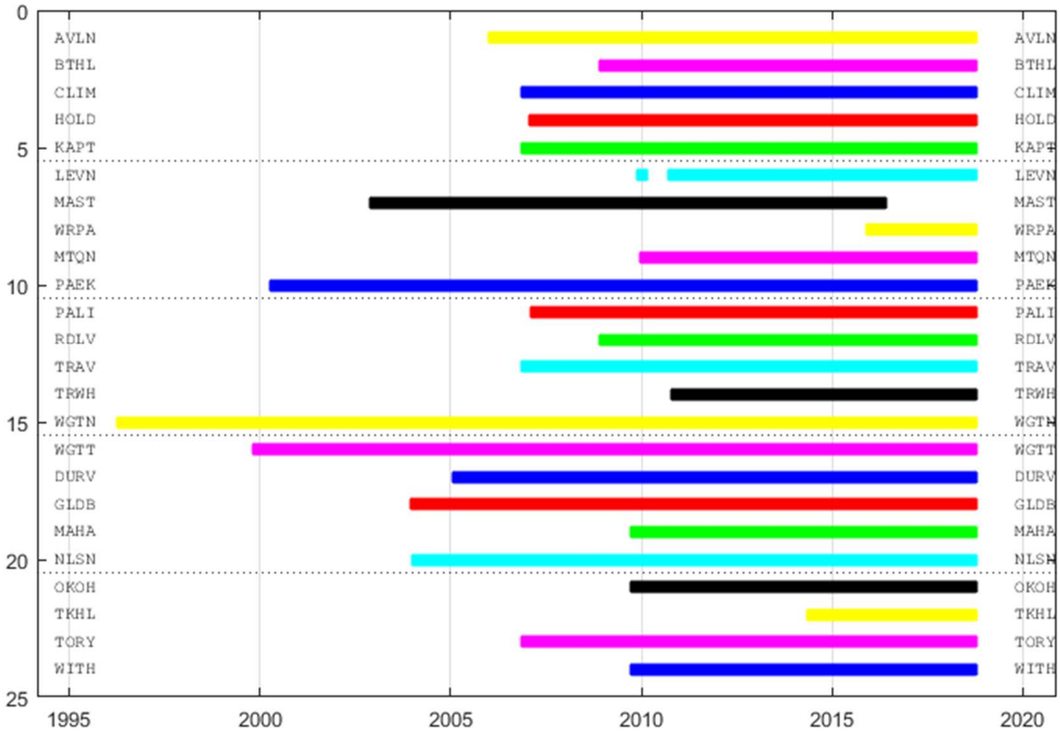

Figure 4-4: Data periods used for each GNSS site in this report. Locations and codes: see Figure 4-5 and https://www.geonet.org.nz/data/network/sensor/map. *Source*: P Denys (Univ. of Otago).

A plot of the GNSS sites is shown in Figure 4-5 together with the secular (long term) horizontal velocities. The effects of seismic events and the current velocity due to the Kaikoura 2016 earthquake, have not been shown.

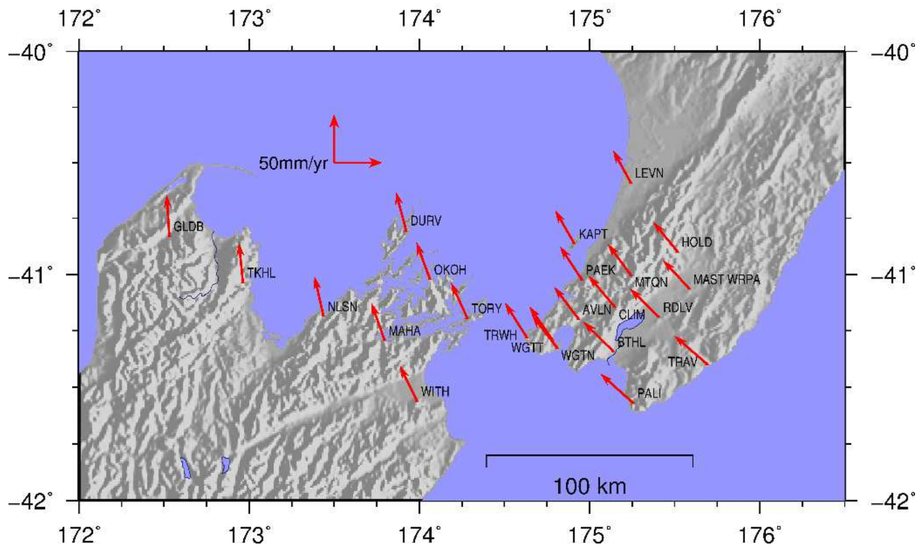

Figure 4-5: Map of the GNSS sites used and the long-term (secular) horizontal velocity. *Source*: P Denys (Univ. of Otago).

4.4 GNSS derived long-term vertical land motion

The GNSS measured vertical rate has been estimated for several sites near Wellington. Sites along the Kāpiti Coast, across to the east coast of the North Island and the top of the South Island have been included. The secular height trend for nine, predominately coastal, sites are shown in Figure 4-6, where tectonic components such as slow slip events, coseismic offsets, and postseismic responses have been removed to isolate the underlying trend without tectonic events (which are unpredictable).

In Figure 4-6, the sites are approximately ordered from LEVN south down the Kāpiti Coast (KAPT) to Terawhiti (TRWH), along the south Wellington coast and north along the east coast (TRAV). The vertical velocities are determined from sites with records between 2000–2018. The site with the shortest monitoring period is Terawhiti (TRWH, 7.7 years).

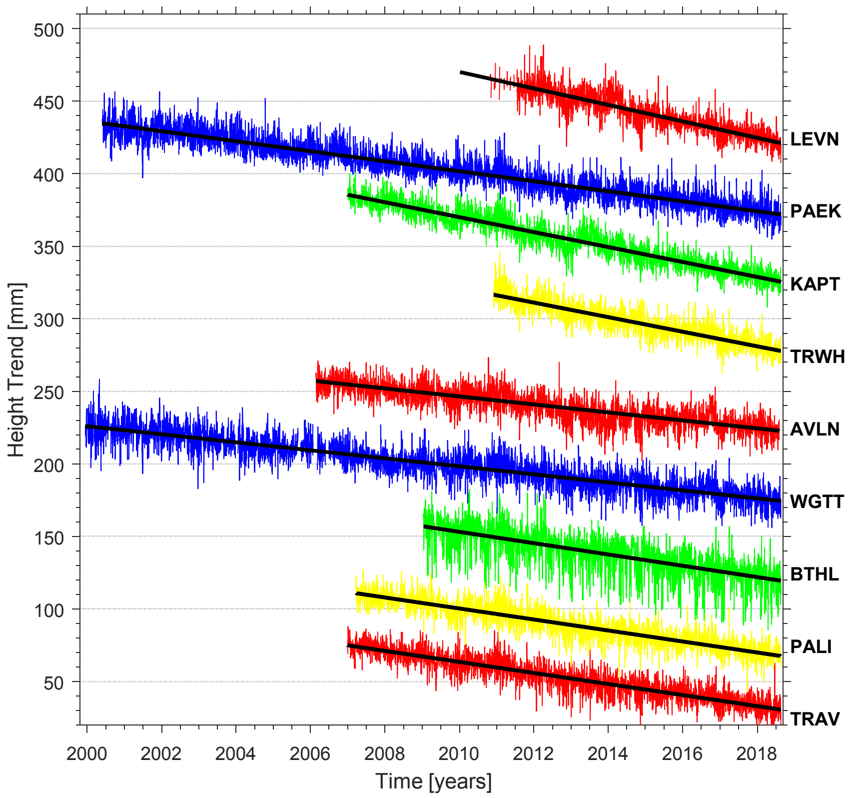

Figure 4-6: Secular height trend for selected coastal GNSS sites. Note: each series is offset for clarity and not to any datum. *Source*: P Denys (Univ. of Otago).

The secular vertical velocity rates for these sites are tabulated in Table 4-1. The range of vertical velocities are between −2.7 mm/year and −5.7 mm/year (i.e., subsidence). The comparative VLM over the broader region is shown in Figure 4-7.

Table 4-1: Secular vertical velocity for selected GNSS sites (excluding seismic displacements). *Source*: P Denys (Univ. of Otago).

Site	Secular vertical velocity (mm/year)	Std. error (mm/year)
AVLN	-2.75	0.14
BTHL	-3.90	0.16
KAPT	-5.15	0.15
LEVN	-5.67	0.17
PAEK	-3.45	0.12
PALI	-3.79	0.15
TRAV	-3.81	0.15
TRWH	-5.02	0.18
WGTT	-2.69	0.12

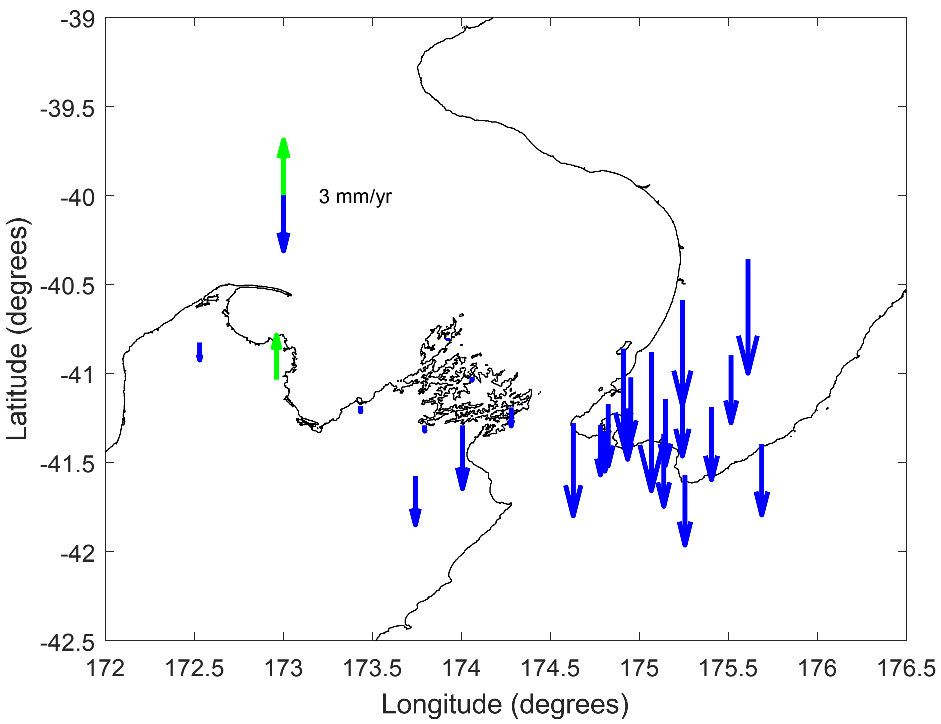

Figure 4-7: Long term (secular) vertical land motion map from cGNSS sites in the lower North Island and upper South Island. *Source*: P Denys (Univ. of Otago).

4.5 Vertical land movement from slow-slip and earthquake events

The GNSS time series are also influenced by seismic activity, comprising slow slip events(SSEs), coseismic deformation (during earthquakes) and post-earthquake crustal response (postseismic and decay) processes.

The east coast of the North Island, Kāpiti Coast and top of the South Island are all affected by periodic slow slip events (SSE) that have, so far, uplifted the land over the period of GPS/GNSS measurements (approximately 20 years). The largest events occurred in 2003, 2008 and 2013. In this case, the Kapiti Coast 2013 SSE was active for approximately 12 months.

Based on the long record cGNSS sites (WGTN, WGTT, PAEK), these events appear to occur every 6–8 years and can last for up to one year. The SSE progressively become larger from the east coast to the west coast, which represents the transition from the Pacific to the Australian plates.

At the GNSS site WGTT, associated with the Wellington Harbour sea-level gauge, the cumulative effect of SSEs over the past decade has been an uplift of ~17 mm (Table 4-2 and Table A-2).

The Wellington region has also been affected by three major earthquake events that were felt during the last five years—Seddon earthquakes (2) in 2013 and Kaikoura on 14 November 2016. In addition, there was a swarm of earthquakes (Wanganui Basin Swarm) orginating to the west on the Kāpiti Coast in late December 2014.

The coseismic deformation resulted in subsidence of a few centimetres in the Wellington region, except for sites on the east coast of the North Island. At the GNSS site WGTT associated with the Wellington Harbour sea-level gauge, the coseismic subsidence immediately after the Kaikoura earthquake was ~20 mm (Table A-2) and a total of 27 mm coseismic subsidence for all earthquakes since 2013 (Table 4-2).

Following the Kaikoura earthquake event, signficant postseismic displacement has occurred up to present, mostly uplift. Some sites along the Kāpiti Coast, have uplifted by approximately 50 mm, negating much of subsidence caused by the coseismic deformation during the Kaikoura earthquake.

At the GNSS site WGTT associated with the Wellington Harbour sea-level gauge, the postseismic and transient velocity displacements since the Kaikoura earthquake have been an uplift of 40 mm (Table 4-2 and Table A-3), and mainly explains the drop in annual MSL in 2017 for the Wellington gauge record (Figure 3-1).

More details of the analysis for these seismic components in the GNSS records are discussed in Appendix A.

4.6 Total vertical displacement

The total displacement experienced in the Greater Wellington region over the GNSS monitoring period is the sum of the individual displacements:

- secular (long term) velocity, $V_S(t - t_0)$
- slow slip events, Δ_{SSE},
- coseismic displacement, $\Delta_{\mathrm{Coseismic}}$, and

- postseismic displacement, $\Delta_{\mathrm{Postseismic}}$ that includes both the postseismic decay and velocity transient.

Equation 4-2: Sum of individual vertical displacements (secular velocity and seismic components).

$$\Delta_{Total} = V_S(t - t_0) + \Delta_{SSE} + \Delta_{Coseismic} + \Delta_{Postseismic}$$

where Δ_{SSE}, $\Delta_{\mathrm{Coseismic}}$, $\Delta_{\mathrm{Postseismic}}$ are the sum of each individual events.

The total displacements are tabulated in Table 4-2 and graphically shown in Figure 4-8 (for the North Island sites only).

The displacement due to the long term (secular) velocity has been computed for a 10-year period (Table 4-2; column 5), as most cGNSS sites have only been operating over the last decade. The first block of rows (Table 4-2) correspond to the North Island sites, the second block of sites correspond to sites in the top of the South Island to provide a wider context. The standard errors of the various components are listed in a small font.

Three cGNSS sites, WGTN, WGTT and PAEK, have been operating for approximately 20 years and the vertical displacements for this period are also given (Table 4-2, last three rows).

Clearly, the entire greater Wellington region is subsiding due to the subducting plate (Pacific) pulling the Australian Plate vertically down. Vertical rates range from nearly zero to over 5 mm/year (equivalent to 50 mm per 10 years). The only site subject to uplift is TKHL near Motueka (+2.4 mm/year), which is further afield in the Tasman region.

For the greater Wellington region (lower North Island), Figure 4-8 shows that both the secular velocity and coseismic displacements were mostly subsidence (range +5 mm to -57 mm, red and orange bars, Figure 4-8). Conversely, the displacement due to the combined postseismic decay and transient velocity following the Kaikoura 2016 earthquake and SSE is mostly uplift (range +53 mm to -2 mm; dark and light green bars, Figure 4-8).

The net effect (Equation 2) is that the subsidence due to the subduction of the Pacific plate under the Australian plate and coseismic displacement to date is mostly cancelled out by the current day Kaikoura earthquake postseismic deformation and the upwards ratcheting effect of the SSEs. The combined (net) effect of all the displacements over the 10-year period is vertical displacements in the range of +21 mm to -33 mm (right hand scale, Figure 4-8 and right-hand column, Table 4-2). It is evident, for the 10-year period 2008–2018, that there is a pattern of net uplift on the Kāpiti Coast of ~20 mm, decreasing to the east where the net subsidence is ~30 mm (i.e., total displacement).

In the case of the three sites with the longest cGNSS records (WGTN, WGTT, PAEK), the (secular) velocity results in greater subsidence overall for the longer 20-year period. As no significant earthquakes were observed during the initial 10 years (1998–2008), the position time series for these sites is mostly affected by the same seismic events as the cGNSS sites with the shorter position time series. The combined effect is subsidence at all three of these longer-term sites of 1–3 centimetres (−13 mm to −27 mm).

Table 4-2: Vertical displacements at GNSS sites. Displacements due to the secular site velocities (mm/year) are computed for 10-year (all sites) and 20-year periods (PAEK, WGTN, WGTT only). Displacements over these time periods are given for secular velocity, earthquake coseismic, post seismic and transient velocities, and slow slip events. The final column gives the cumulative net effect of the secular velocity displacements and seismically-induced displacements. S_u is standard error.

					Seismically-induced displacements							Seismic
Site	Site 2*	Secular Velocity (mm/year)	s_H	Secular displacement (mm)	Coseismic (mm)	s_H	Postseismic (mm)	Tran. vel (mm)	SSE (mm)	s_H	Sub-total (mm)	+ Secular (mm)
10 years												
AVLN		-2.75	0.14	-28	-6	9.1	27	2	15	2.6	38	10
BTHL		-3.90	0.16	-39	-18	24.4	40	-9	0	0.0	14	-25
CLIM		-3.57	0.15	-36	-6	9.6	10	9	13	2.8	27	-9
HOLD		-3.65	0.15	-37	-41	21.4	38	-13	19	6.2	3	-33
KAPT		-5.15	0.15	-52	-24	7.3	34	15	46	2.0	72	21
LEVN		-5.67	0.17	-57	-25	5.9	28	3	38	3.7	44	-12
MAST	WRPA	-2.99	0.13	-30	5	6.3	6	1	-2	1.9	9	-21
MTQN		-4.45	0.17	-45	-7	9.8	17	7	16	3.4	32	-13
PAEK		-3.45	0.12	-35	-17	8.8	27	11	32	5.1	54	19
PALI		-3.79	0.15	-38	11	3.6	13	1	0	0.0	25	-13
RDLV		-3.94	0.16	-39	0	11.7	7	0	0	0.0	8	-32
TRAV		-3.81	0.15	-38	5	7.3	11	0	0	0.0	15	-23
TRWH		-5.02	0.18	-50	-8	5.5	33	20	21	6.0	66	16
WGTN		-2.17	0.11	-22	-7	6.4	35	1	7	4.7	37	15
WGTT		-2.69	0.12	-27	-27	8.6	37	3	17	4.8	30	3
South Is												
DURV		-0.02	0.14	0	-14	5.7	-2	-9	-24	5.9	-49	-49
GLDB		-0.94	0.13	-9	5	5.7	15	-5	-5	5.9	9	0
MAHA		-0.31	0.17	-3	-29	5.5	20	-9	-5	5.9	-23	-27
NLSN		-0.32	0.13	-3	-7	4.7	-4	-8	-19	2.0	-38	-41
OKOH		-0.18	0.17	-2	-16	5.2	7	-7	-14	2.7	-31	-32
TKHL		2.39	0.25	24	-9	8.0	5	-12	0	0.0	-16	8
TORY		-0.99	0.15	-10	-44	7.6	48	-2	-10	5.3	-7	-17
WITH		-0.29	0.17	-3	58	4.9	96	-9	-11	7.9	134	131
20 years												
PAEK		-3.45	0.12	-69	-17	8.8	27	11	41	3.9	51	-18
WGTN		-2.17	0.11	-43	-7	6.4	35	1	2	4.1	30	-13
WGTT		-2.69	0.12	-54	-27	8.6	37	3	17	4.8	26	-27

* Site 2: sites that are collocated and have been modelled as a single site. *Source*: P. Denys, Univ. of Otago.

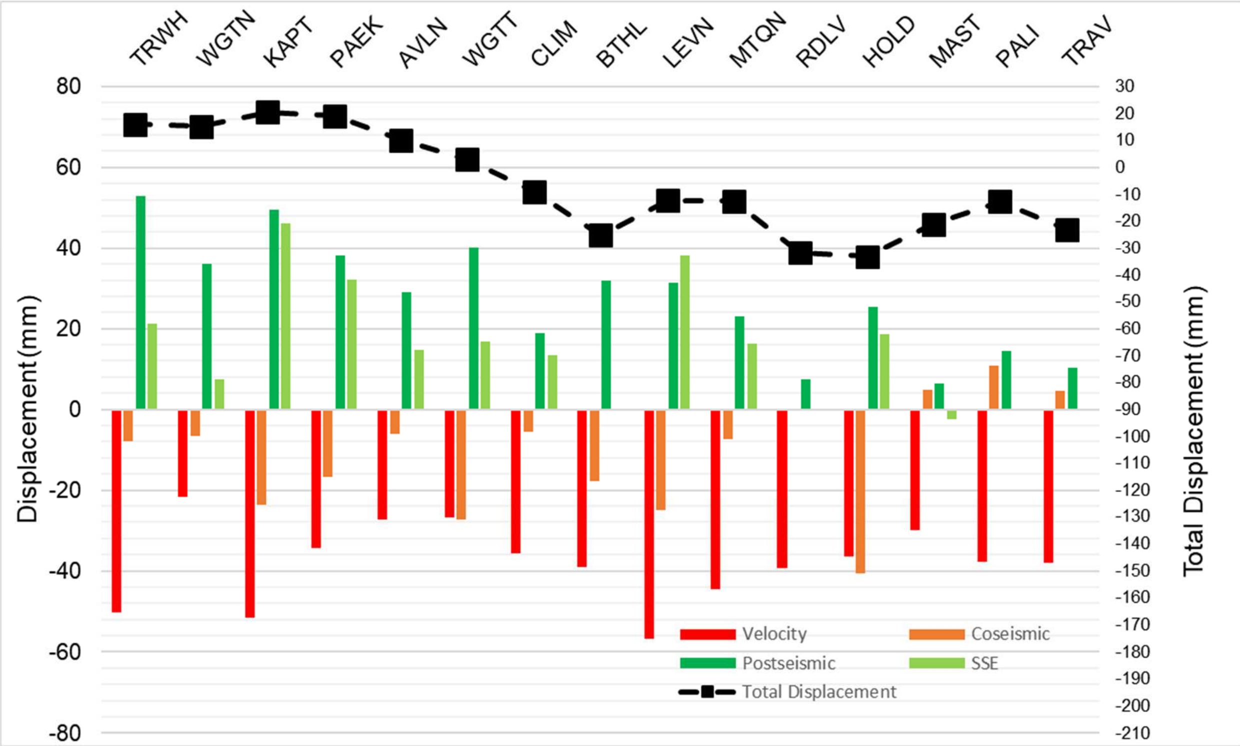

Figure 4-8: Vertical displacements at cGNSS sites in the Wellington region computed over 10 years (2008–2018). The individual components (secular velocity, coseismic, postseismic, SSE) (left scale) and total (net) displacement (right scale), with sites ordered approximately from west to east. *Source*: P Denys (Univ. of Otago).

4.7 Long-term trend and implications of results

4.7.1 Long-term VLM trends

It is difficult to provide a definitive long-term trend of VLM for any site in the Wellington region, largely due to the effects and ongoing influences on crustal movement of the recent earthquake events since 2013. What the GNSS position data does show, is that the deformation in this region is complex and is likely to remain so in the future. While the subducting plate continues to incrementally pull both the Pacific and Australian plates down (subsidence), this is offset upwards by periodic SSE and the recent Kaikoura earthquake event.

What is also clear, is that the recent major earthquake events (Seddon 2013 and Kaikoura 2016), both displaced the Wellington region. The effect of coseismic displacement was subsidence by up to 40 mm, while (ongoing) postseismic displacement is causing ongoing uplift of up to 50 mm to date. In addition, the region is affected by the occasional SSE that (typically) results in uplift, which has amounted to over 40 mm.

At the GNSS site WGTT associated with the Wellington Harbour sea-level gauge, the postseismic and transient velocity displacements since the Kaikoura earthquake have been an uplift of 40 mm (Table 4-2 and Table A-2), and mainly explains the drop in annual MSL in 2017 for the Wellington gauge record (Figure 3-1).

A summary of the VLM in the greater Wellington region, as observed by the cGNSS sites in the lower North Island for the 10-year period (2008–2018), is as follows:

- Secular Velocity Displacement:
  - 2 – 5 mm/year background subsidence (punctuated by seismic displacements up or down).
  - Long term trend of subsidence (although GNSS monitoring only started in the late 1990s).
  - The region is undergoing subduction along the Hikurangi Margin subduction zone as the thick oceanic Hikurangi Plateau is subducting beneath the continental crust of the Australian plate.
- Coseismic Displacement:
  - 0 – 40 mm subsidence for sites on the west side of the Rimutaka Range and Kāpiti Coast.
  - 0 – 10 mm uplift for sites on the east side of the Rimutaka Range and east coast of the North Island.
  - These instantaneous displacements arise from sufficiently large earthquakes such as Seddon 2013 and Kaikoura 2016.
- Postseismic Displacement:
  - 10 – 50 mm uplift increasing from the east coast of the North Island to the Kāpiti Coast.
  - The combined effect of postseismic decay and a post-earthquake transient velocity due to the Kaikoura 2016 earthquake is generating uplift. It is expected that the displacement may continue for many years albeit the displacement will gradually become smaller over time.
- Slow Slip Events (SSE) Displacement:
  - 0 – 45 mm uplift that increases from the east coast of the North Island to the Kāpiti Coast.
  - Periodic events that appear to occur in approximately 5-8 years cycle results in VLM ratcheting upwards.

4.7.2 Implications of VLM on RSLR for the Wellington region

The MfE Coastal Guidance (MfE, 2017; Section 5.3) outlined previous analyses and maps by Beavan and Litchfield (2012) to provide guidance of VLM around New Zealand. This work only covered the early part of the GNSS records (up to early 2012) and predates the major earthquakes and SSEs in recent years.

The updated results for the Wellington region in this Report demonstrate the complexities of VLM in the region and how the background secular (long-term) subsidence can be punctuated by significant seismic displacements, up or down, from SSEs and earthquake coseismic and postseismic processes.

While it is possible to estimate the secular subsidence (long term) and estimate with less certainty the SSE rate; it is not possible to estimate the displacement of future earthquake events, and therefore is difficult to incorporate into long-term land-use planning for RSLR.

However, the dynamic adaptive pathways planning (DAPP) approach adopted in MfE Coastal Guidance can also cover the uncertainty posed by unknown future seismic VLM. The DAPP process maps out alternative pathways or adaptation options, and then monitoring progress towards pre-defined triggers (or decision points) before switching pathways for a coastal area. Monitoring (e.g., number of damaging floods, SLR reached, insurance withdrawn etc.,) and reviewing the situation over the intervening time are crucial elements of this adaptive approach so that the switch to another pathway is undertaken in a timely manner—not too early, and not too late.

Therefore, the "monitor and review" step in the DAPP approach, lends itself to the complexity exhibited in the VLM time series to date in the Wellington region and what the future might hold. For example, if VLM secular trend changes substantially or there is another major earthquake event, then the switch to the next pre-planned pathway could be delayed or brought forward considering the changes in VLM, as well as the other factors/indicators including SLR and other risk indicators.

The results in this report highlight the critical role of GNSS and MSL monitoring in the Wellington region and the urgent need nationally to bolster long-term GNSS monitoring systems specifically in coastal areas—especially actively tectonic areas or those urban or peri-urban areas subject to ongoing subsidence (e.g., sedimentary basins such as former river deltas, groundwater pumping, large-scale drainage networks in low-lying areas). LINZ currently are coordinating efforts to investigate the co-location of several sea-level gauges in New Zealand with GNSS monitoring to improve the coverage (compared with the extensive GeoNet network which is focused on tectonic effects).

Finally, the previous recommendation (Bell & Hannah, 2012) to update the analyses of RSLR and VLM at 5-yearly intervals is justified by the findings of this report and should continue at similar intervals, with a more rigorous assessment undertaken every 10 years.

5 Acknowledgements

Greater Wellington Regional Council and LINZ are acknowledged as the sources of the sea-level data from the Wellington Harbour gauge.

The GNSS time series data was sourced from GeoNet (GNS Science) and funded in part by LINZ (PositioNZ sites).

6 Glossary of abbreviations and terms

cGNSS	Continuous monitoring station sampling satellite signals in the Global Navigation Satellite System.
coseismic	The immediate displacement of the land surface soon after an earthquake.
DAPP	Dynamic adaptive pathways planning approach adopted in MfE (2017).
ENSO	El Niño–Southern Oscillation climate mode that occurs over a two- to five-year cycle, mainly in the Pacific.
GNSS	Global Navigation Satellite System..
GPS	Global Positioning System: USA satellite system
GWRC	Greater Wellington Regional Council.
IPCC	Intergovernmental Panel on Climate Change – a scientific and intergovernmental body under the auspices of the United Nations.
IPO	Inter-decadal Pacific Oscillation, which is a longer-term ENSO-like mode that occurs over a 20- to 30-year cycle, mainly in the Pacific. The IPO switched to the negative phase around 1999.
LINZ	Land Information NZ.
MSL	Average (mean) level of the sea relative to a vertical datum over a defined epoch, usually annually to several years. Baseline MSL for IPCC sea-level rise projections is the average over the 20-year period 1986–2005.
NZVD2016	NZ Vertical Datum 2016 (national vertical datum established by LINZ in 2016)
postseismic	The ongoing crustal displacement (months to years) after an earthquake and its initial coseismic response.
RSLR	Relative sea-level rise.
SLR	Sea-level rise.
VLM	Vertical land motion (displacements or rates of movement).
WVD-53	Wellington Vertical Datum – 1953. The regional land datum for the Wellington region.

7 References

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Appendix A Seismic components of vertical land motion

Further details are provided on the seismic components and offsets in the GNSS records for the Wellington region and the wider region including upper South Island. Sites are shown in Figure 4-5.

A.1 Slow-slip events (SSEs)

The east coast of the North Island, Kāpiti Coast and top of the South Island are all affected by periodic slow slip events (SSE) that have, so far, uplifted the land over the period of the GPS/GNSS measurements (approximately 20 years). Based on the longer record cGNSS sites (WGTN, WGTT, PAEK), these events appear to occur every 6–8 years and can last for up to one year. The SSE progressively become larger from the east coast to the west coast, which represents the transition from the Pacific to the Australian plates.

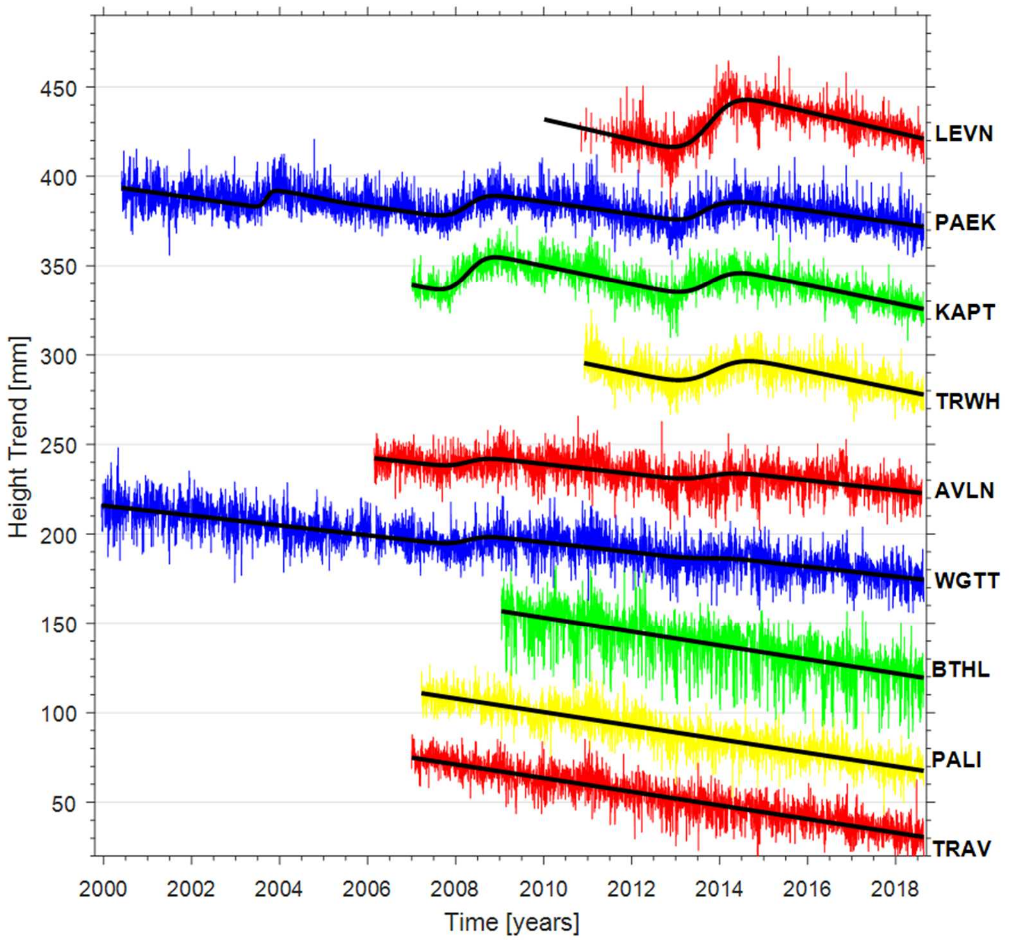

Figure A-1: Slow slip events have uplifted (to date) the Australian plate relative to the Pacific plate at GNSS sites in Wellington region. *Source*: P Denys (Univ. of Otago).

Figure A-1 shows the vertical displacements or offsets that have occurred during SSEs over the GNSS monitoring period. The largest events have occurred in 2003, 2008 and 2013. In this case, the Kāpiti Coast 2013 SSE was active for approximately 12 months.

Figure A-2 and Figure A-3 show the effect of the Kāpiti Coast 2013 SSE only. While the vertical component is pertinent to this project, the horizontal displacement (Figure A-3) is also given to illustrate the total effect of this SSE. Table A-1 lists the individual displacements for SSEs and the cumulative totals for the last decade and for the three longer-term sites, for 20 years.

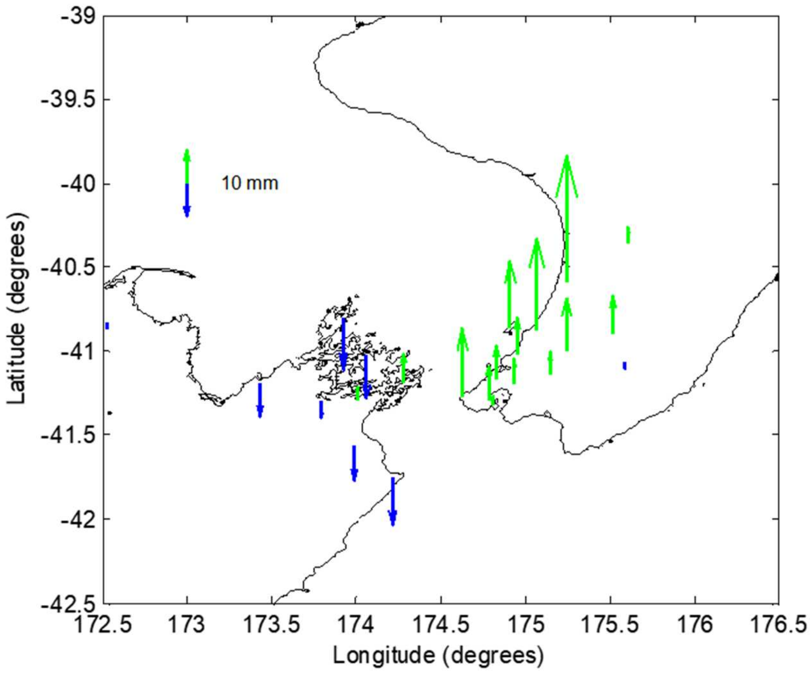

Figure A-2: The vertical displacement caused by the Kāpiti Coast 2013 SSE. *Source*: P Denys (Univ. of Otago).

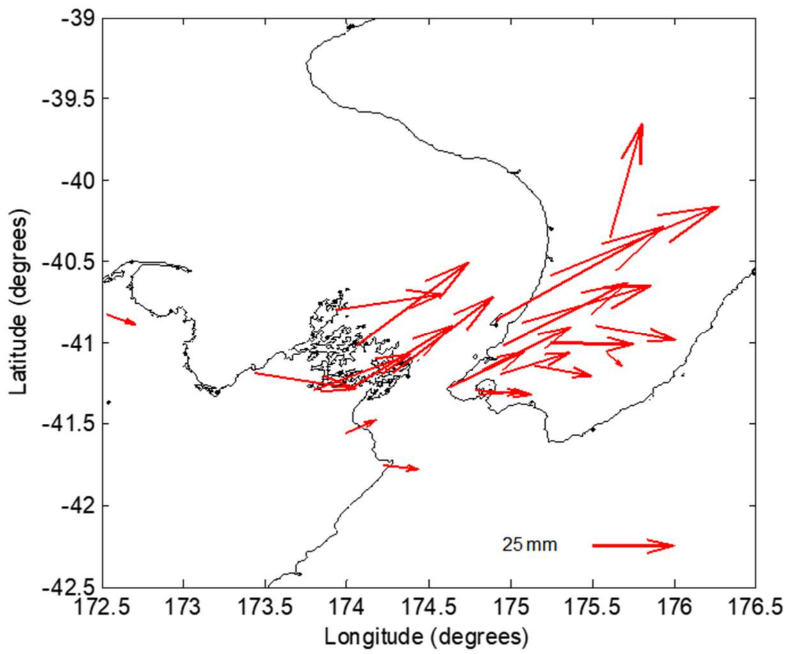

Figure A-3: Horizontal displacement caused by the Kāpiti Coast 2013 SSE. Note the general pattern of the motion: anticlockwise and increasing magnitude pattern of the western sites, and a mostly eastern and small magnitude displacement of the eastern sites along a line that starts in the Wairarapa basin. *Source*: P Denys (Univ. of Otago).

Table A-1: Vertical displacements at GNSS sites for SSEs since 1999. The cumulative total displacement has been determined for a total of 10 years and 20 years (only 3 sites). S_H is the standard error. *Source*: P Denys (Univ. of Otago).

		Kāpiti Coast 1999.749		Kāpiti Coast 2003.696		Kāpiti Coast 2004.864		Kāpiti Coast 2005.238		Kāpiti Coast 2008.270		Kāpiti Coast 2013.852		Kāpiti Coast 2015.127		SSE Total 10 years		SSE Total 20 years	
Site	**Site2***	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H	**(mm)**	s_H
AVLN										7.4	2.5	7.4	2.7			**14.8**	2.6		
CLIM										6.5	2.8	7.0	2.8			**13.5**	2.8		
DNVK								20.5	2.1					36.3	2.5	**36.3**	2.5	**56.8**	2.3
DURV										-8.5	1.9	-15.8	2.1			**-24.3**	2.0		
HOLD										6.9	6.2	11.7	6.2			**18.6**	6.2		
KAPT										26.1	1.9	20.2	2.0			**46.3**	2.0		
LEVN												38.1	3.7			**38.1**	3.7		
MAHA												-5.5	5.9			**-5.5**	5.9		
MAST	WRPA											-2.4	1.9			**-2.4**	1.9		
MTQN												16.2	3.4			**16.2**	3.4		
PAEK				10.7	2.0	-1.6	2.2			16.2	2.2	15.8	6.9			**32.1**	5.1	**41.2**	3.9
TRWH												21.2	6.0			**21.2**	6.0		
WGTN		-5.2	2.4							4.5	1.9	3.0	6.4			**7.5**	4.7	**2.3**	4.1
WGTT										6.6	2.4	10.3	6.4			**16.8**	4.8		
WITH												-10.7	7.9			**-10.7**	7.9		

* Site 2: sites that are collocated and have been modelled as a single site.

At the GNSS site WGTT associated with the Wellington Harbour sea-level gauge, the cumulative effect of SSEs over the past decade has been an uplift of ~17 mm (Table A-1).

A.2 Earthquake events

The Wellington region has been affected by 3 major earthquake events that were felt during the last five years.

In addition, there was a swarm of earthquakes originating to the west on the Kāpiti Coast (Wanganui Basin Swarm) in late December 2014. The dates of these events are (square brackets in decimal years):

- Seddon EQ1 2013 [Cook Srait]: 21/7/2013 [2013.551]
- Seddon EQ2 2013 [Grassmere]: 16/8/2013 [2013.622
- Wanganui Basin Swarm: 30/12/2014 [2013.995]
- Kaikoura 2016: 13/11/2016 [2016.866]

Following a major earthquake effect, deformation occurs as an instantaneous displacement (coseimsic offset) followed by longer term postseismic deformation that can continue for a few weeks to years. As the Kaikoura earthquake was a large event, the postseismic motion is ongoing even after 20 months and will continue for many more years. The fastest motion occurs immediately after the earthquake event (e.g., centimetres per month for sites on the east coast of the South Island) but will gradually decrease over time. Although the postseismic deformation may be small for any one-year period, the cumulative displacement can be significant.

Coseismic deformation resulted in subsidence of the Wellington region (Figure A-4 and Figure A-5), except for sites on the east coast of the North Island (TRAVE and PALI). Most sites subsided by a few centimetres during the Kaikoura earthquake. Table A-2 lists the individual coseismic displacements for earthquake events and the cumulative coseismic totals over the GNSS records. At the GNSS site WGTT associated with the Wellington Harbour sea-level gauge, the coseismic subsidence during the Kaikoura earthquake was ~20 mm (Table A-2).

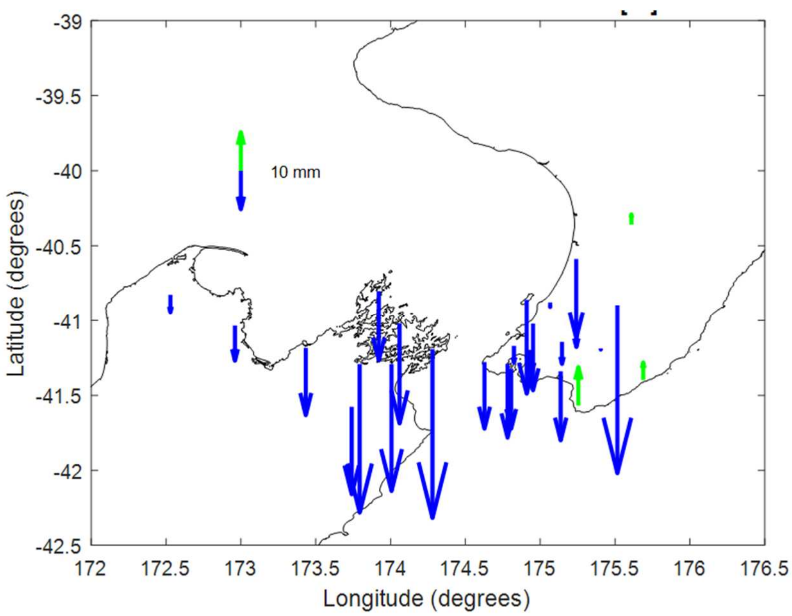

Figure A-4: Vertical coseismic displacement caused by the Kaikoura Nov 2016 earthquake. *Source*: P Denys (Univ. of Otago).

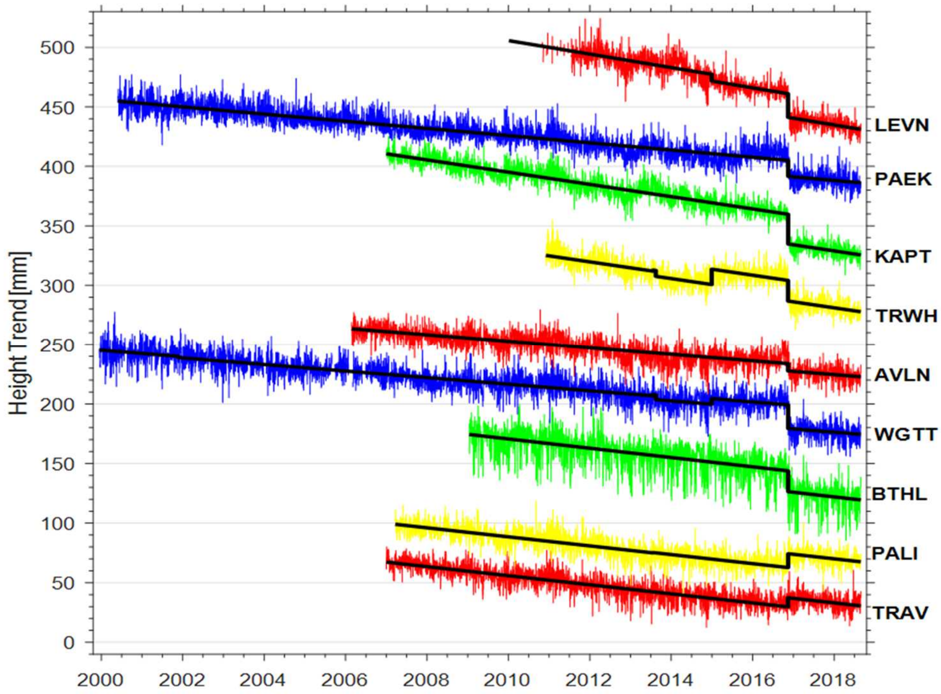

Figure A-5: Height time series including the vertical coseismic displacement. Offsets can be seen for the Seddon earthquakes (2013.551, 2013.622) and the Kaikoura earthquake. *Source*: P Denys (Univ. of Otago).

Table A-2: Vertical coseismic displacements caused by earthquake events since 2013. Source: P. Denys (Univ. of Otago). S_H is the standard error.

		Seddon EQ1 2013.551		Seddon EQ2 2013.622		Wanganui Basin 2014.995		Kaikoura 2016 2016.866		Total displacement	
Site	Site 2*	(mm)	s_H	(mm)	s_H	(mm)	s_H	(mm)	s_H	(mm)	s_H
AVLN								-6.2	9.14	**-6.2**	9.1
BTHL								-17.9	24.4	**-17.9**	24.4
CLIM								-5.6	9.58	**-5.6**	9.6
DURV						4.4	1.58	-18.4	7.85	**-14.0**	5.7
GLDB						9.3	1.79	-4.8	7.86	**4.5**	5.7
HOLD								-40.7	21.35	**-40.7**	21.4
KAPT								-23.7	7.31	**-23.7**	7.3
LEVN						-5.7	2.31	-19.3	8.04	**-25.0**	5.9
MAHA		0.9	5.34	-5.5	5.74	13.3	1.92	-38.1	7.57	**-29.4**	5.5
MAST	WRPA					8.2	2.07	-3.3	9.68	**4.9**	7.0
MRL1								-22.1	6.75	**-22.1**	6.8
MTQN								-7.3	9.79	**-7.3**	9.8
NLSN						10.4	1.53	-17.8	6.47	**-7.4**	4.7
OKOH						9.5	1.69	-26.0	7.12	**-16.5**	5.2
PAEK								-16.7	8.75	**-16.7**	8.8
PALI		0.3	1.55					10.5	4.83	**10.8**	3.6
RDLV								0.2	11.68	**0.2**	11.7
TKHL								-9.4	8.04	**-9.4**	8.0
TORY		1.1	7.26	-7.6	7.84	6.3	2.91	-43.7	10.46	**-43.9**	7.6
TRAV								4.7	7.25	**4.7**	7.3
TRWH		0.9	5.28	-4.9	5.66	12.9	2.17	-16.8	7.57	**-8.0**	5.5
WGTN		1.0	6.18	-2.4	6.64	10.1	2.13	-15.2	8.76	**-6.6**	6.4
WGTT		-1.5	7.13	-5.7	7.75			-20.1	10.51	**-27.3**	8.6
WITH		-6.0	4.48	-10.0	4.83	9.3	2.45	64.6	6.81	**57.8**	4.9

Following the Kaikoura earthquake event, up to present, significant postseismic deformation has occurred. This effect has been modelled as a logarithmic decay function plus a transient velocity term. The logarithmic function accounts for the rapidly changing velocity (direction and magnitude) following the event, while the transient velocity accounts for the longer-term velocity change following the event.

Figure A-6 and Figure A-7 shows the predominant uplift of the region following the Kaikoura 2016 earthquake. Table A-3 lists the vertical postseismic displacements and transient velocity displacements (V_H) caused by earthquake events since 2013 for the GNSS sites. Some sites, along the Kāpiti Coast, have uplifted by approximately 50 mm since the Kaikoura earthquake (to date, a rate of +30 mm/year).

At the GNSS site WGTT associated with the Wellington Harbour sea-level gauge, the postseismic and transient velocity displacements since the Kaikoura earthquake has been an uplift of 40 mm (Table A-3), and mainly explains the drop in annual MSL in the Wellington gauge (Figure 3-1).

Overall, the postseismic uplift in the Wellington region since the Kaikoura earthquake up to present has negated much of the subsidence caused by the coseismic deformation immediately after the earthquake.

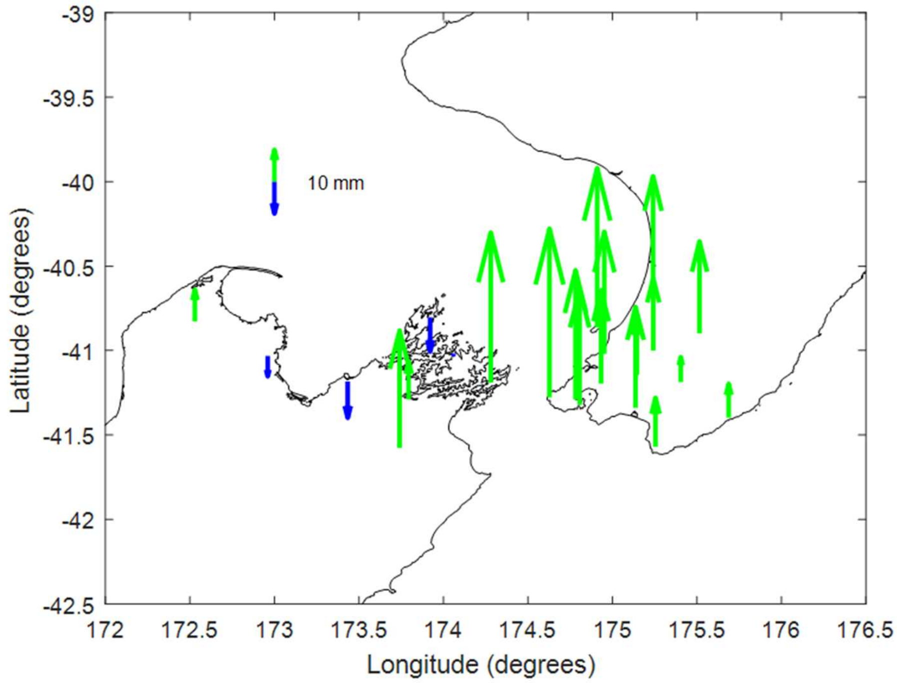

Figure A-6: Vertical postseismic offset and transient velocity since the Kaikoura Nov 2016 earthquake. *Source*: P Denys (Univ. of Otago).

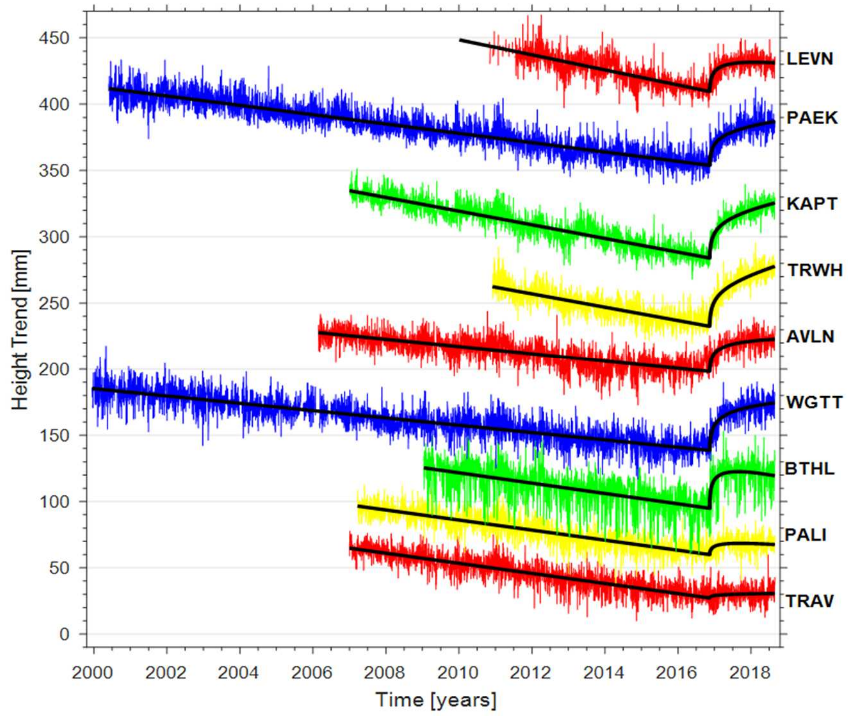

Figure A-7: Height time series including the postseismic decay and velocity displacement (uplift) following the Kaikoura 2016 earthquake. Note: The corresponding coseismic displacement (Figure A-5) has not been plotted. *Source*: P Denys (Univ. of Otago).

Table A-3: Vertical postseismic displacements and transient velocity (V_H) displacements caused by earthquake events since 2013. Source: P. Denys (Univ. of Otago).

Site	Site 2*	Seddon EQ1 2013.551 (mm)	Kaikoura 2016 2016.866 (mm)	Kaikoura 2016 V_H (mm)	Total displacement (mm)
AVLN			26.7	2.3	29.0
BTHL			40.5	-8.7	31.8
CLIM			9.8	9.1	18.9
DURV			-2.2	-8.8	-11.0
GLDB			14.5	-4.8	9.75
HOLD			38.4	-12.9	25.5
KAPT			34.1	15.4	49.6
LEVN			28.3	2.9	31.2
MAHA			20.3	-8.9	11.4
MAST	WRPA		5.7	0.8	6.4
MRL1			37.4	-1.2	36.2
MTQN			16.5	6.6	23.1
NLSN			-3.9	-7.6	-11.5
OKOH			6.7	-7.3	-0.6
PAEK			27.0	11.2	38.2
PALI			12.9	1.5	14.4
RDLV			7.4	0.1	7.5
TKHL			5.4	-12.3	-6.8
TORY			48.5	-2.0	46.5
TRAV			10.5	-0.1	10.4
TRWH			33.2	19.7	52.9
WGTN			34.5	1.5	36.0
WGTT			36.8	3.5	40.3
WITH		16.6	79.1	-8.7	87.0

* Site 2: sites that are collocated and have been modelled as a single site.